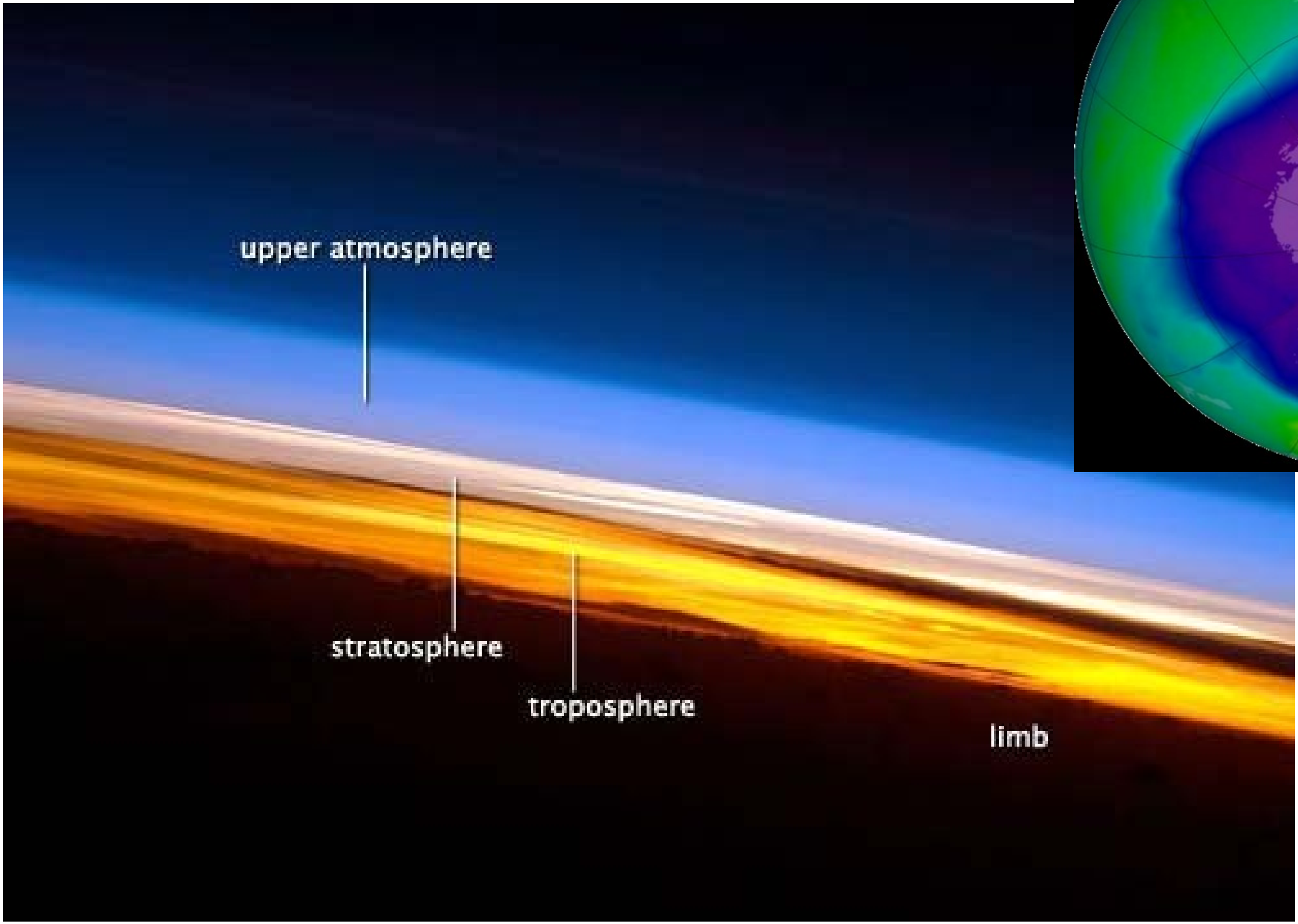
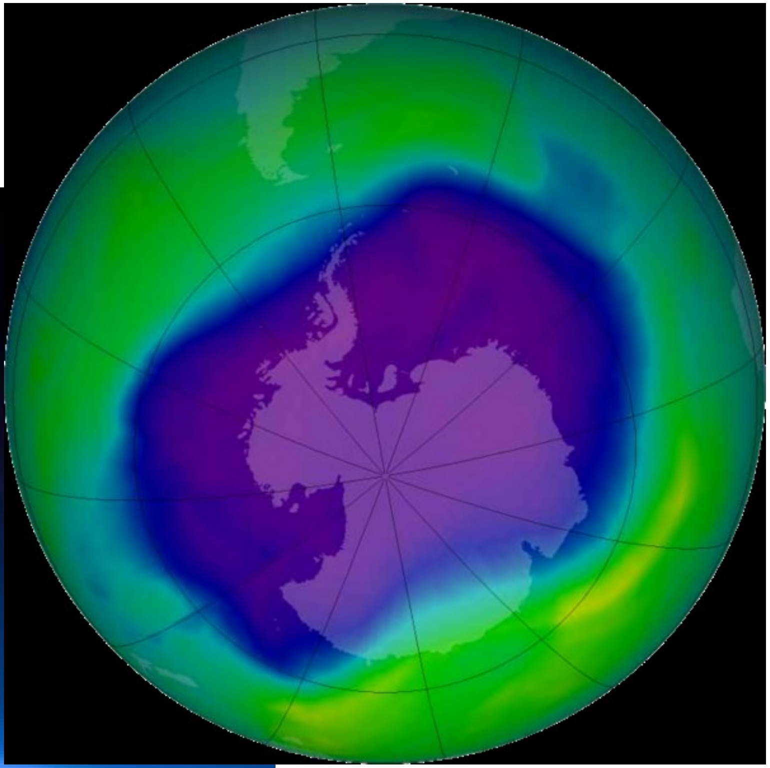
The Stratosphere & the Ozone Hole

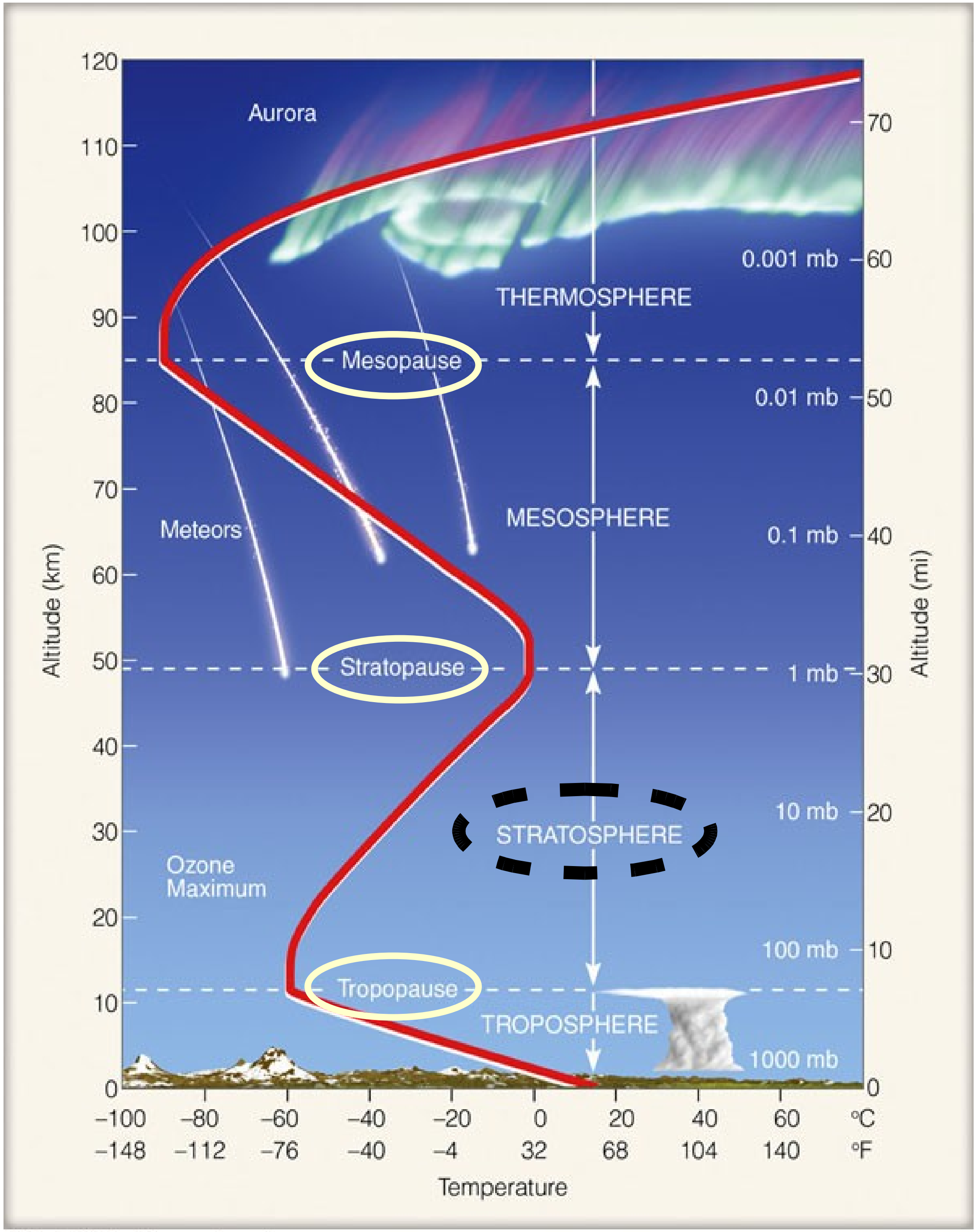




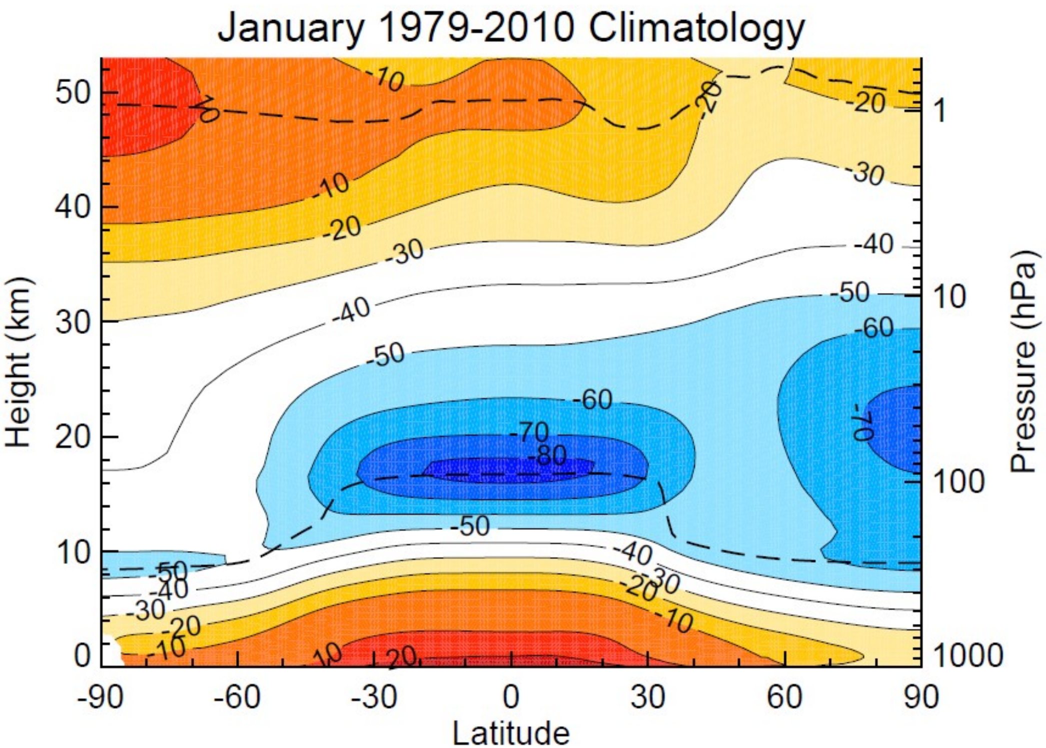
Temperature Structure

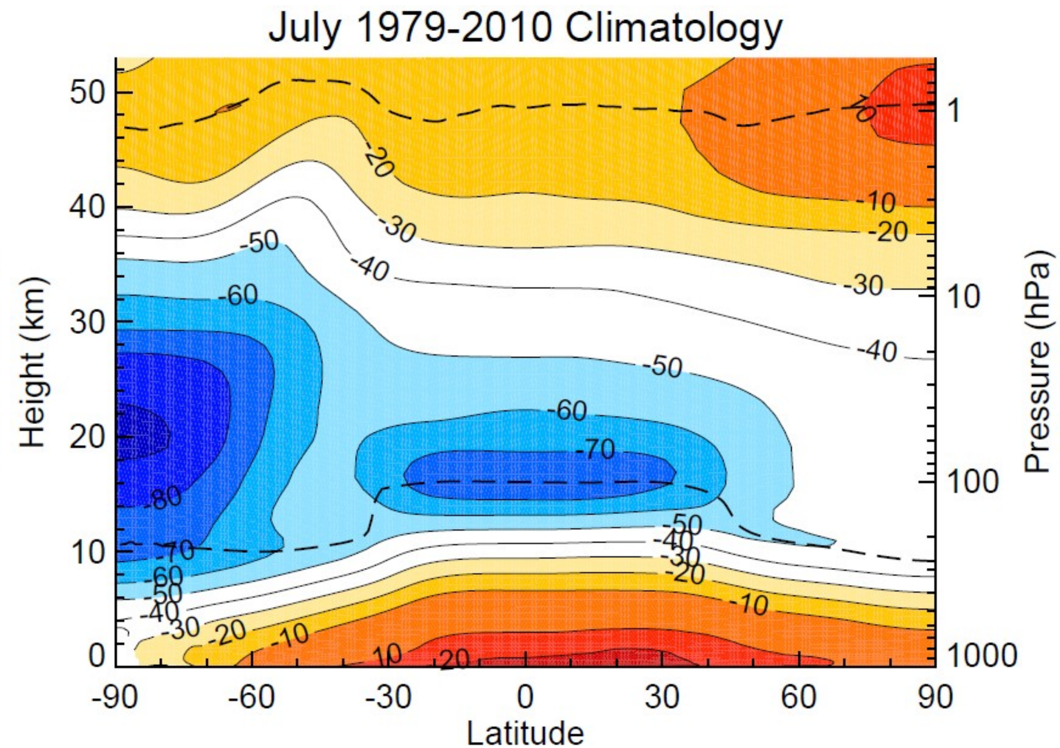
- The atmosphere is layered according to its temperature structure
- In some layers temperature increases with height
- In others it decreases with height or is roughly constant

...”pause” is a level
...“sphere” is a layer



Air Temperature Structure



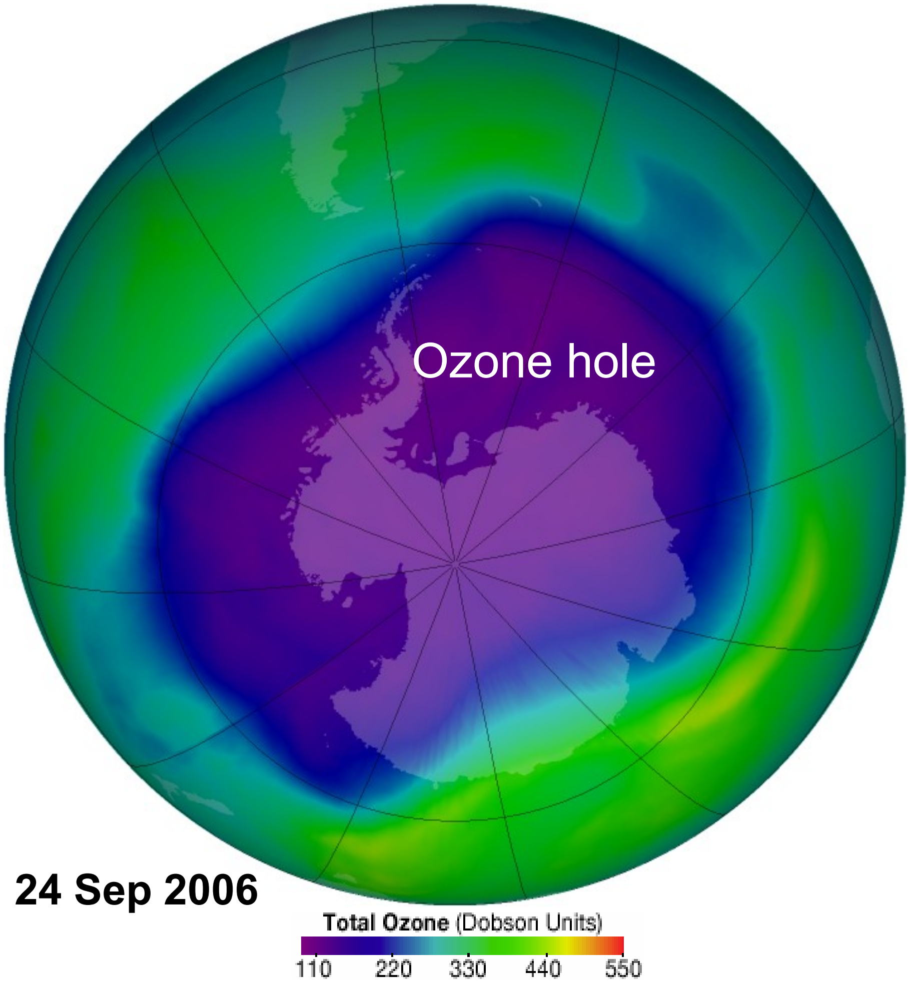


- Cold (and high) tropical tropopause
- Temperature keeps on decreasing into the stratosphere during polar winter
- Southern polar winter much colder than northern polar winter

Contour values are in °C, long dashed lines mark the tropopause and stratopause, respectively.

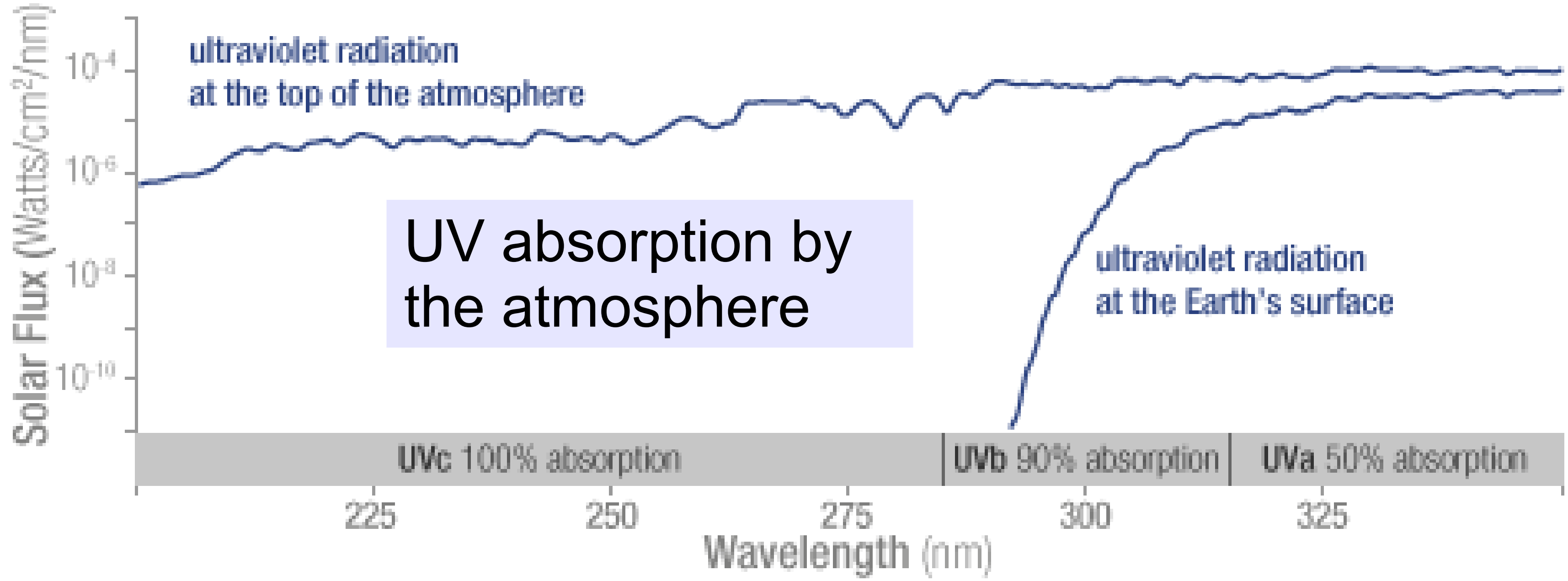
Ozone (O_3)

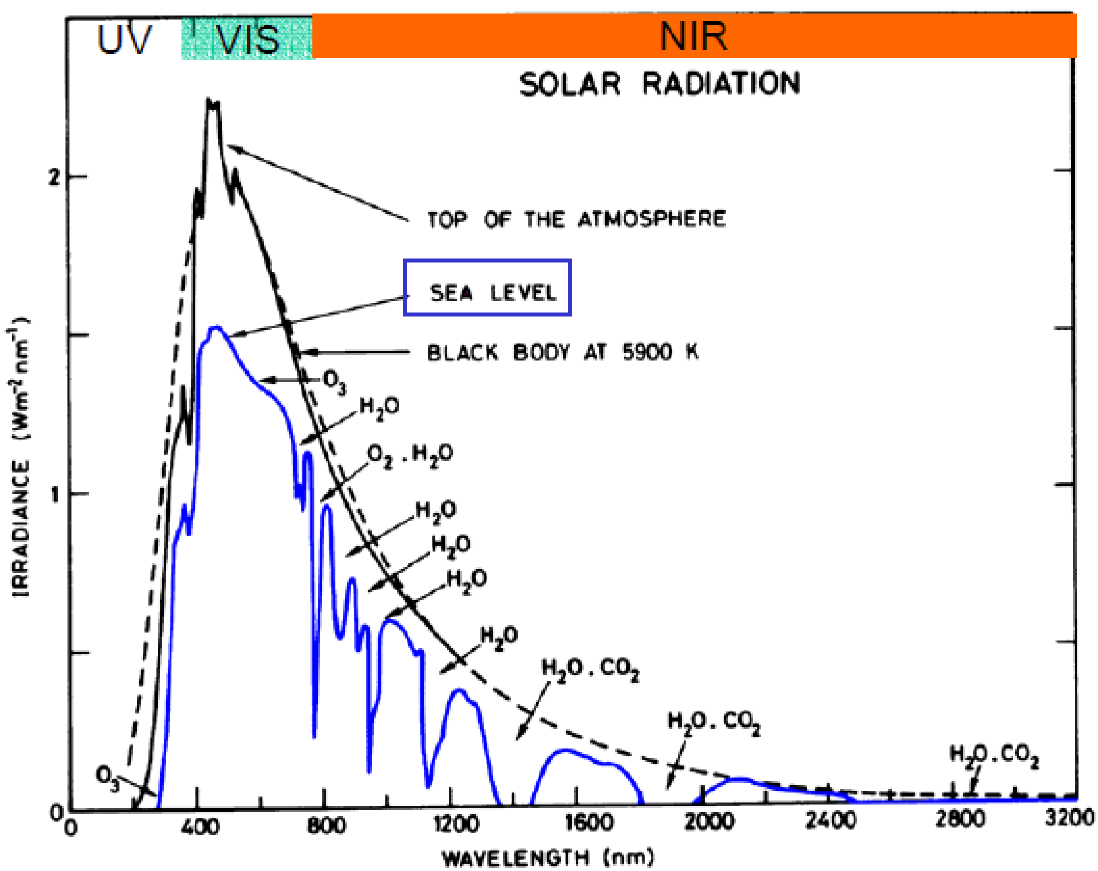
- Why is it good for us?
- Why is it bad for us?
- How is it formed?
- How is it destroyed?



24 Sep 2006

http://ozonewatch.gsfc.nasa.gov/



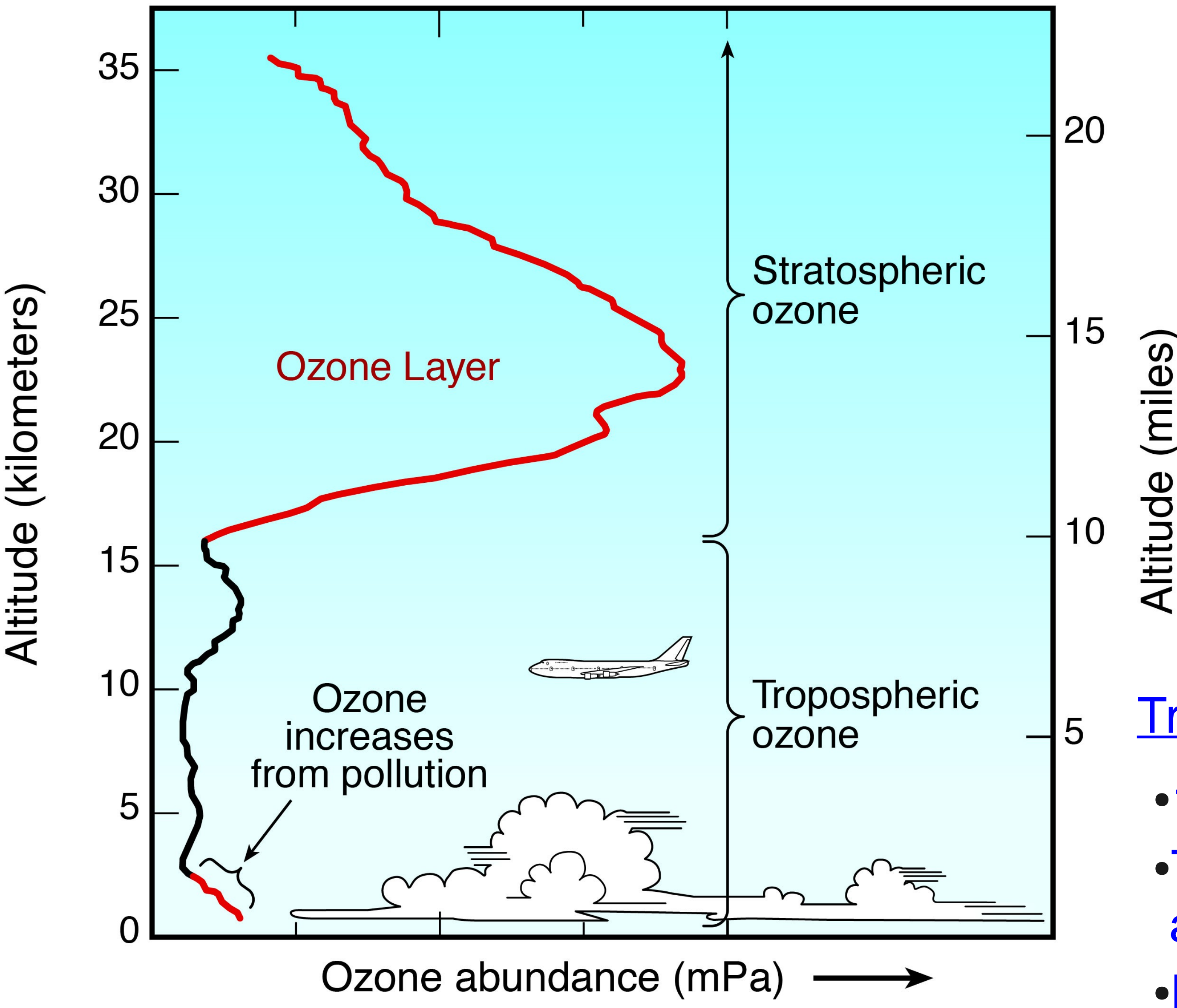


Brasseur & Solomon (1986)

Selective Absorption by Variable Gases

- ~50% of incoming solar radiation is absorbed at the surface
- albedo is ~30% → ~20% of incoming radiation is absorbed by the atmosphere (O_3, CO_2, H_2O, clouds)

Ozone Vertical Structure



WMO Ozone Assessment 2010, Q&A, NOAA

Stratosphere:

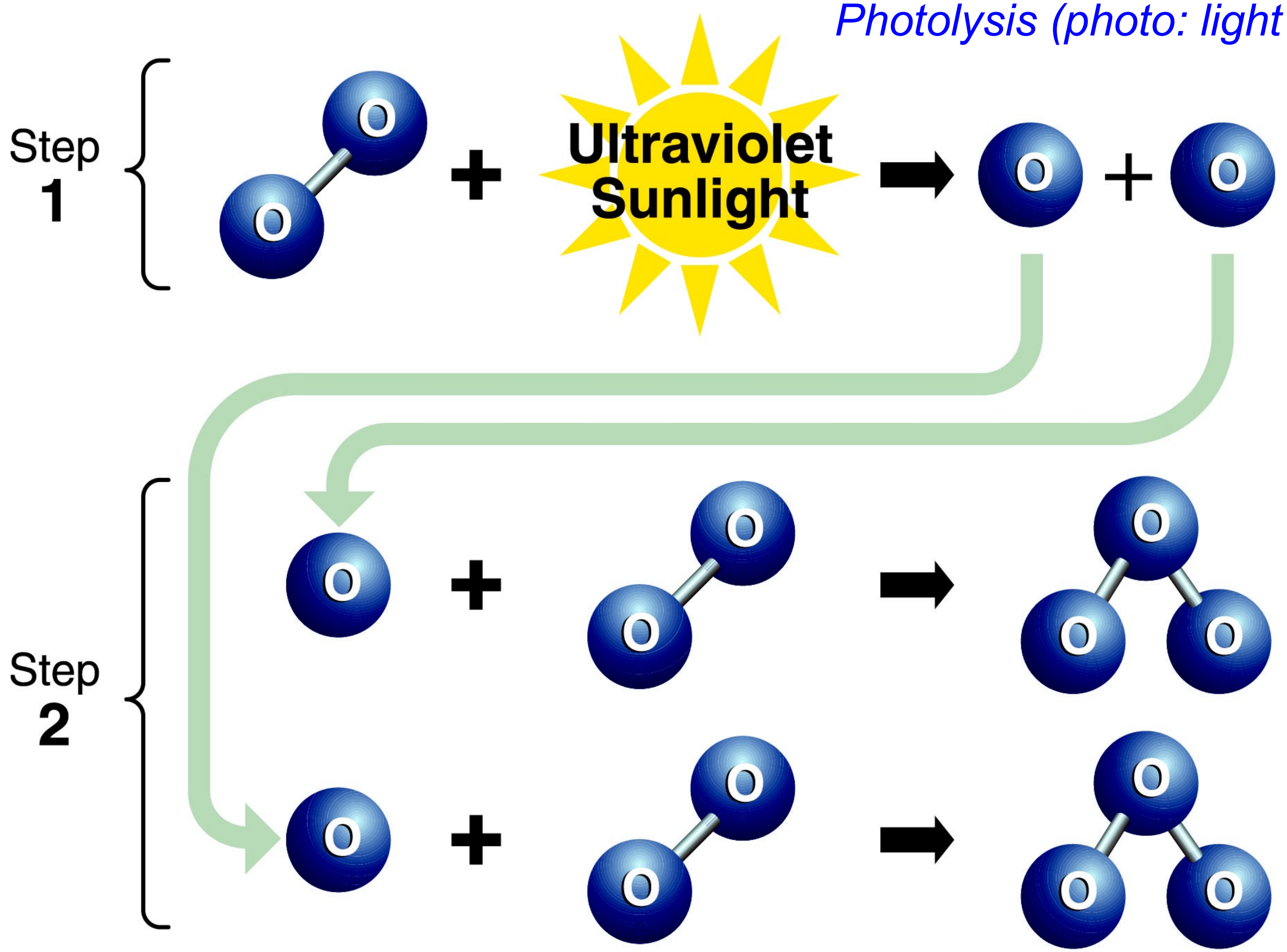
- 90% of atmospheric Ozone
- Primary UV radiation shield
- Springtime Antarctic Ozone Hole

Troposphere:

- 10% of atmospheric Ozone
- Toxic effects on humans and vegetation
- Episodes of high surface Ozone in urban and rural areas

(Simplified) Stratospheric Ozone Production

Photolysis (photo: light + lysis: splitting)



WMO Ozone Assessment 2010, Q&A, NOAA

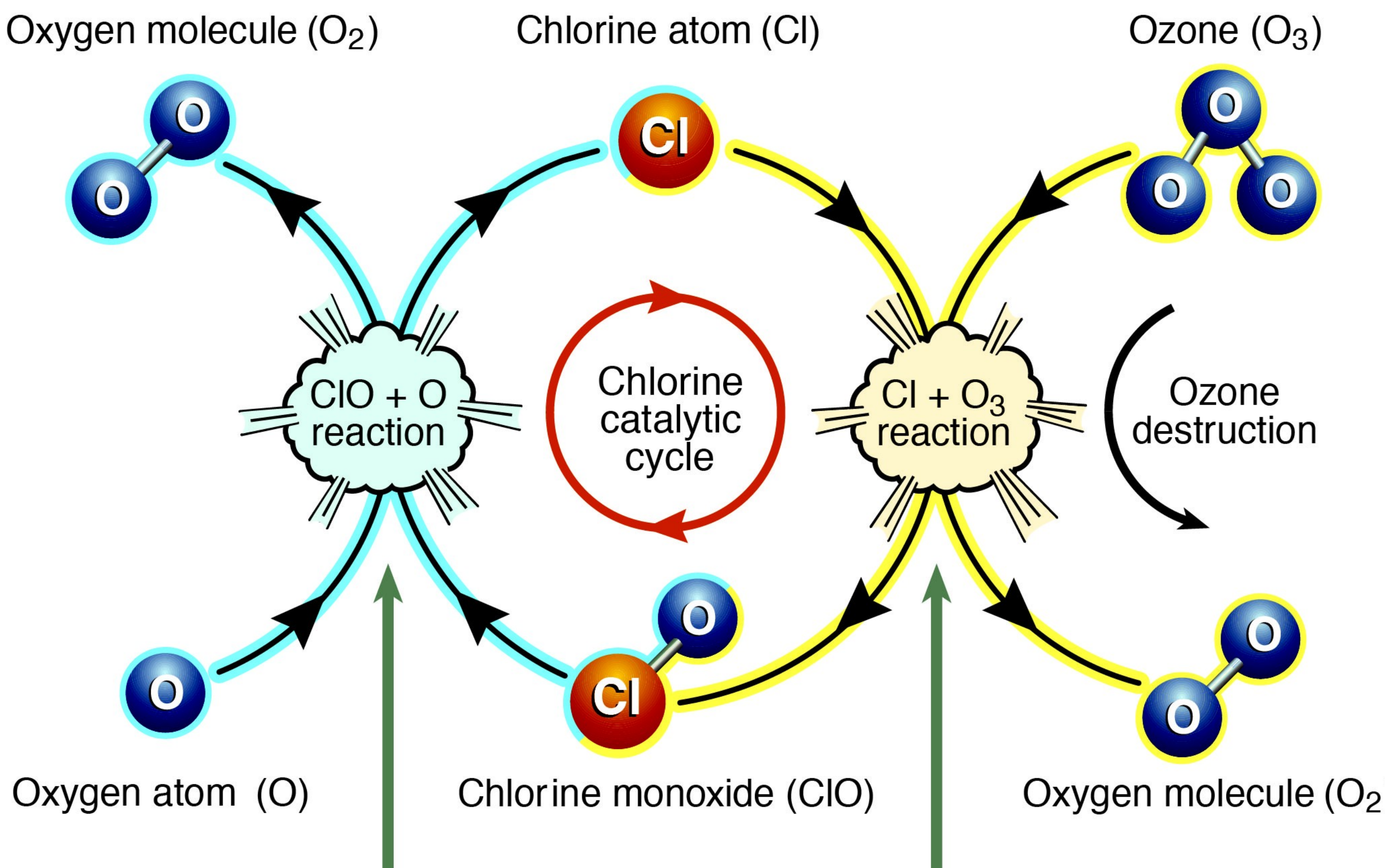
Overall reaction: $3\,O_2 \xrightarrow{\text{sunlight}} 2\,O_3$

Net: UV → Heat (this is why temperature increases with height in the stratosphere)

Catalytic Ozone Destruction

Catalyst: accelerates reaction without being consumed itself

Ozone Destruction Cycle 1



$$Cl + O_3 \rightarrow ClO + O_2$$

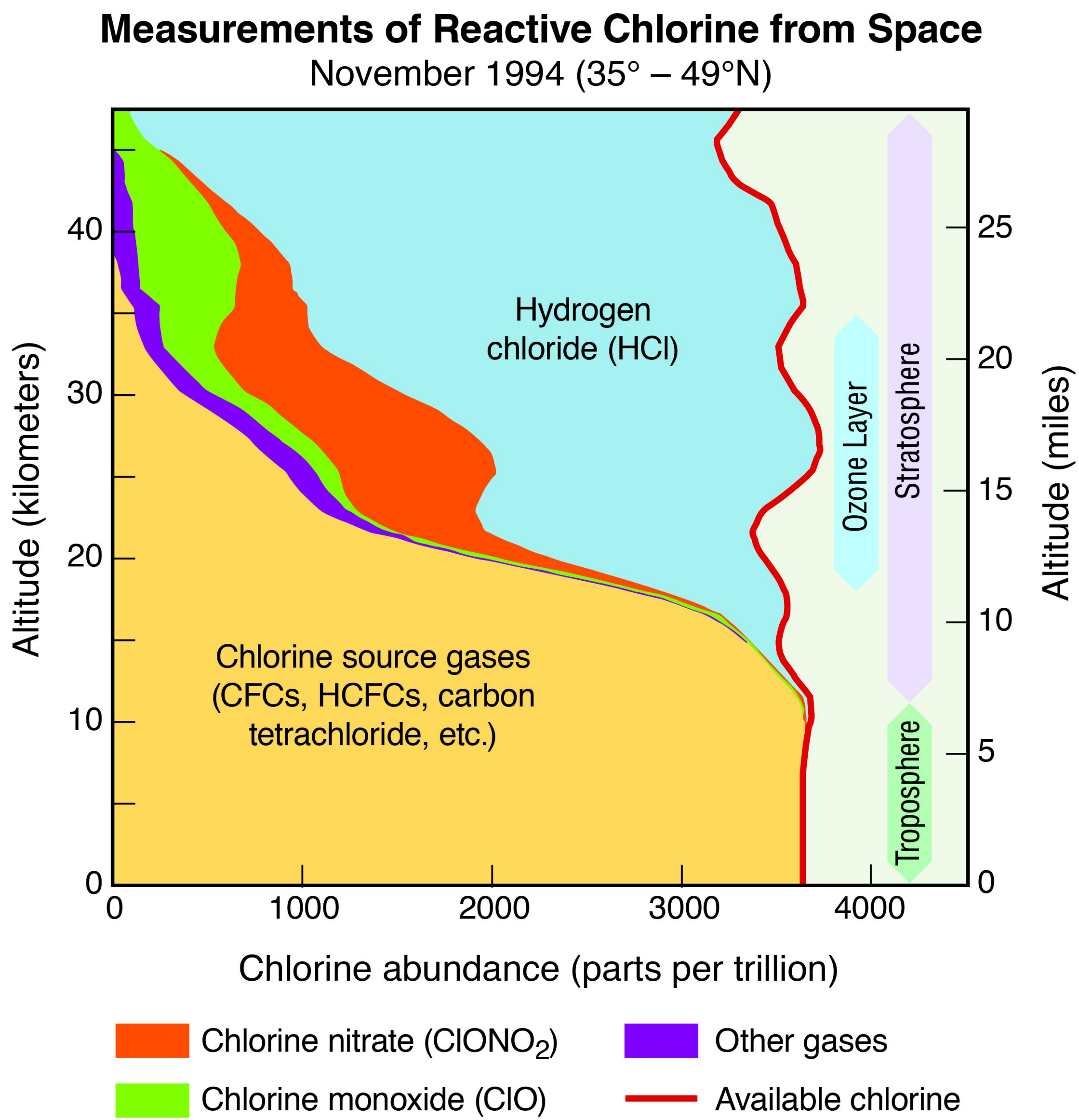
$$ClO + O \rightarrow Cl + O_2$$

$$\text{Net: } O + O_3 \rightarrow 2O_2$$

WMO Ozone Assessment 2010, Q&A, NOAA

Clorofluorocarbons (CFCs)

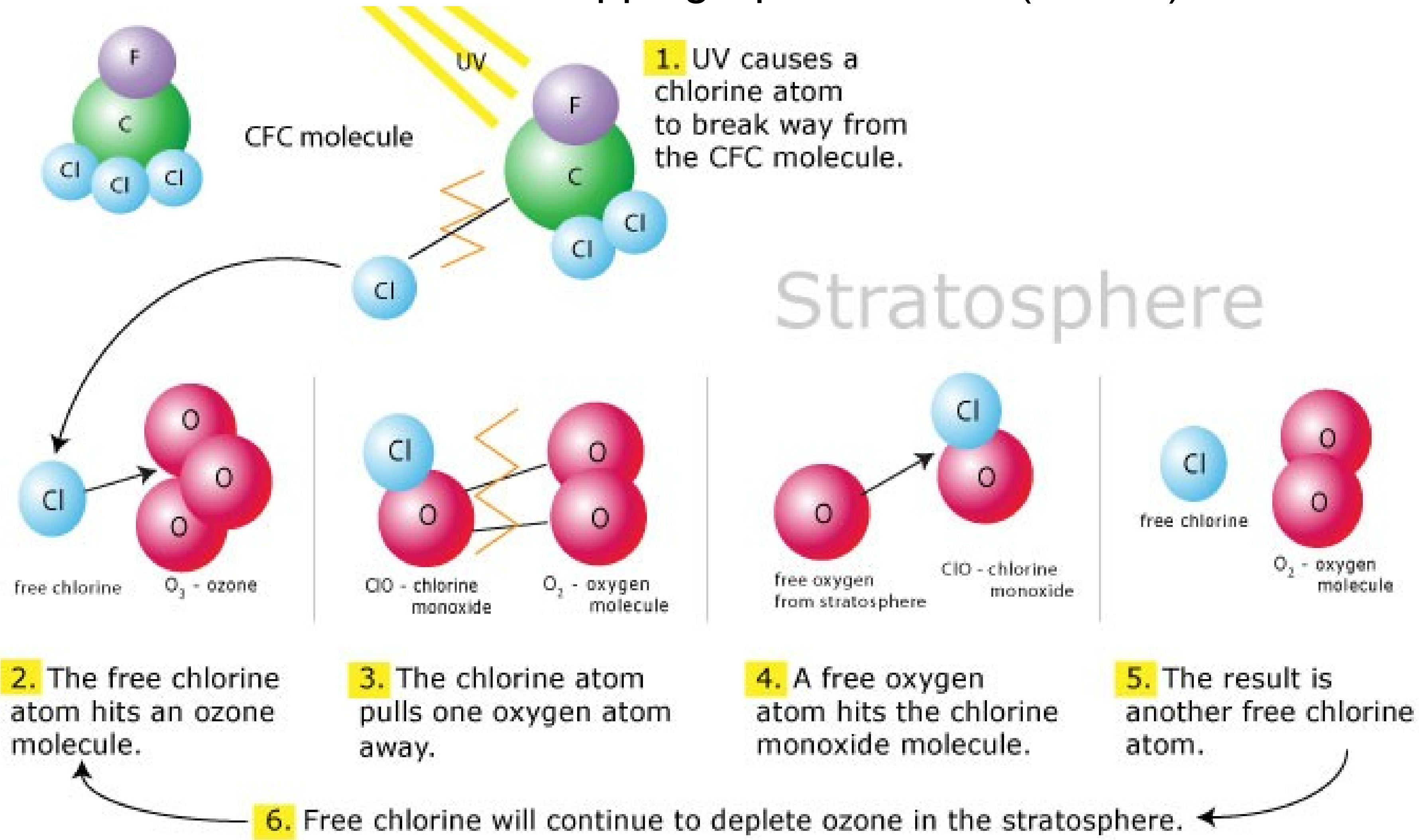
- Also similar halons (bromine compounds)
- Refrigerants, propellants (e.g. aerosol spray), solvents
- Non-reactive = inert → non-toxic
- Inert → they accumulate in the atmosphere
- Lifetimes: CFC-12 (CCl_2F_2) – 100 years, CFC-11 (Ccl_2F) – 45 years
- CFCs are broken up by UV radiation in stratosphere to produce Chlorine nitrate ($ClONO_2$), Chlorine monoxide (ClO), Hydrogen chloride (HCl), and other gases



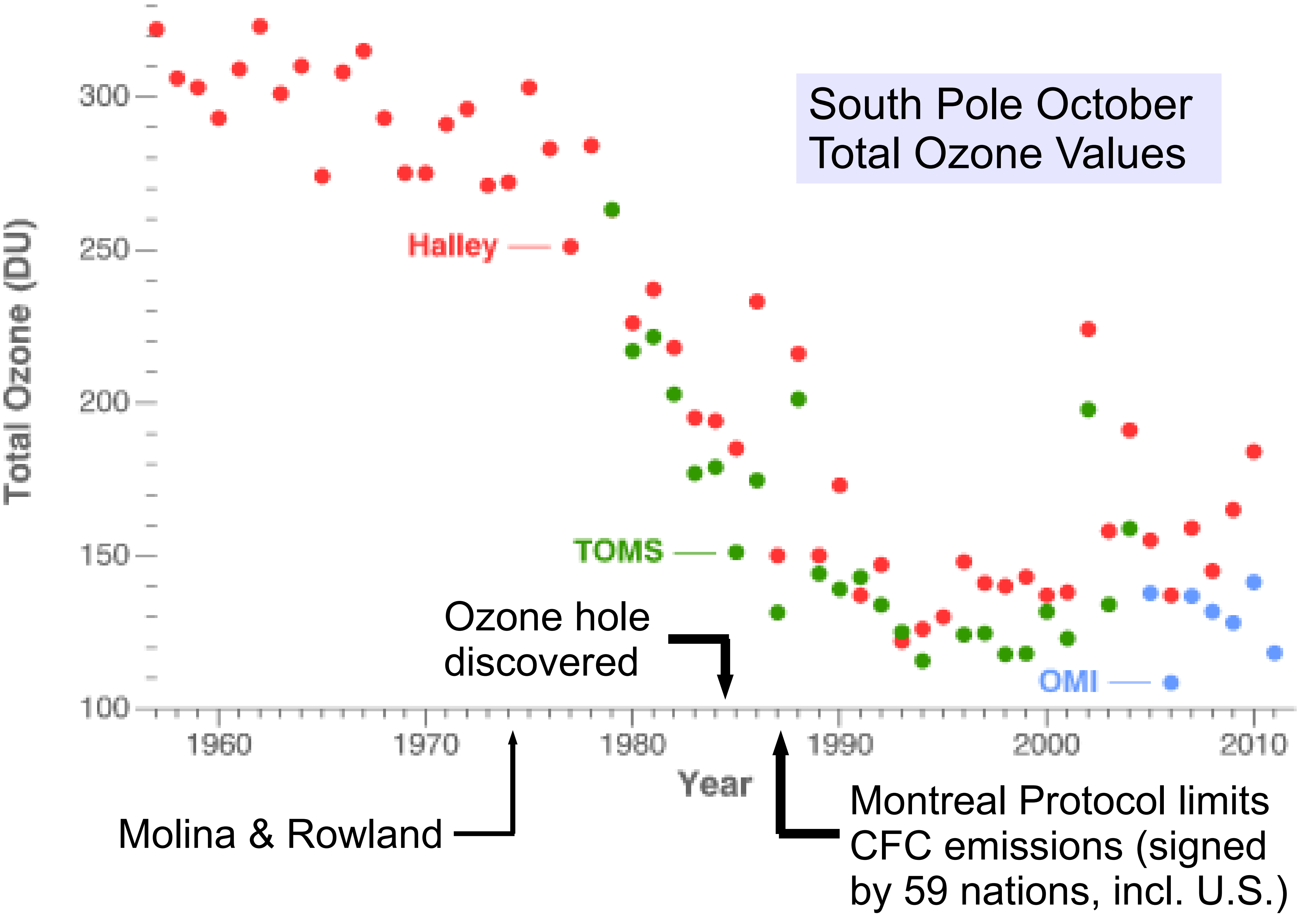
WMO Ozone Assessment 2010, Q&A, NOAA

CFCs & Enhanced Catalytic Ozone Destruction

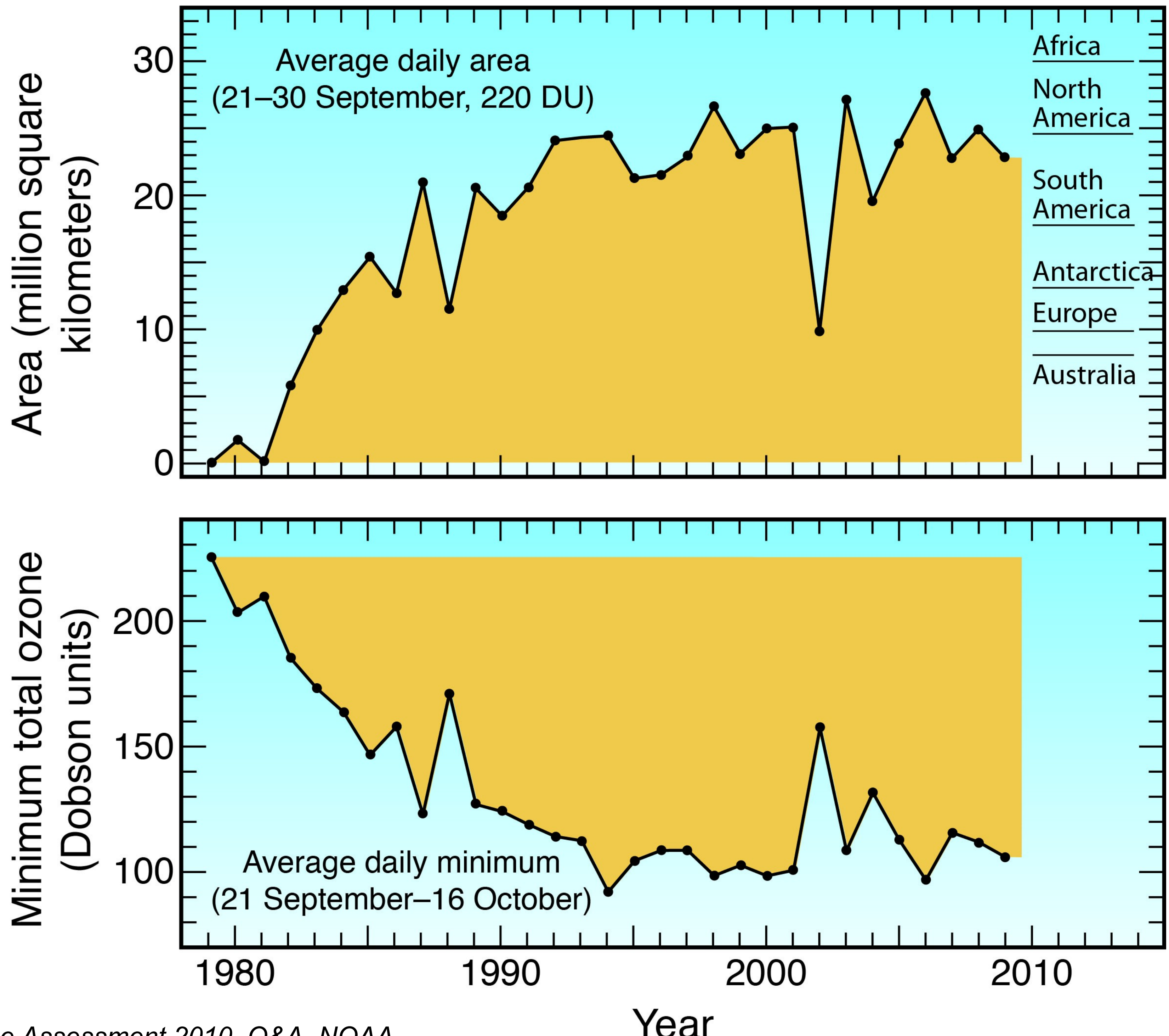
- CFCs provide extra Cl atoms that spin up ozone destruction
- (only) 7% ozone depletion by ~2050 based on studies in mid to late 1970's (most famously Molina & Roland, Nature 1974)
- U.S. Bans CFC use in aerosol sprays in 1978
- NASA launches Total Ozone Mapping Spectrometer (TOMS) Satellite in 1979



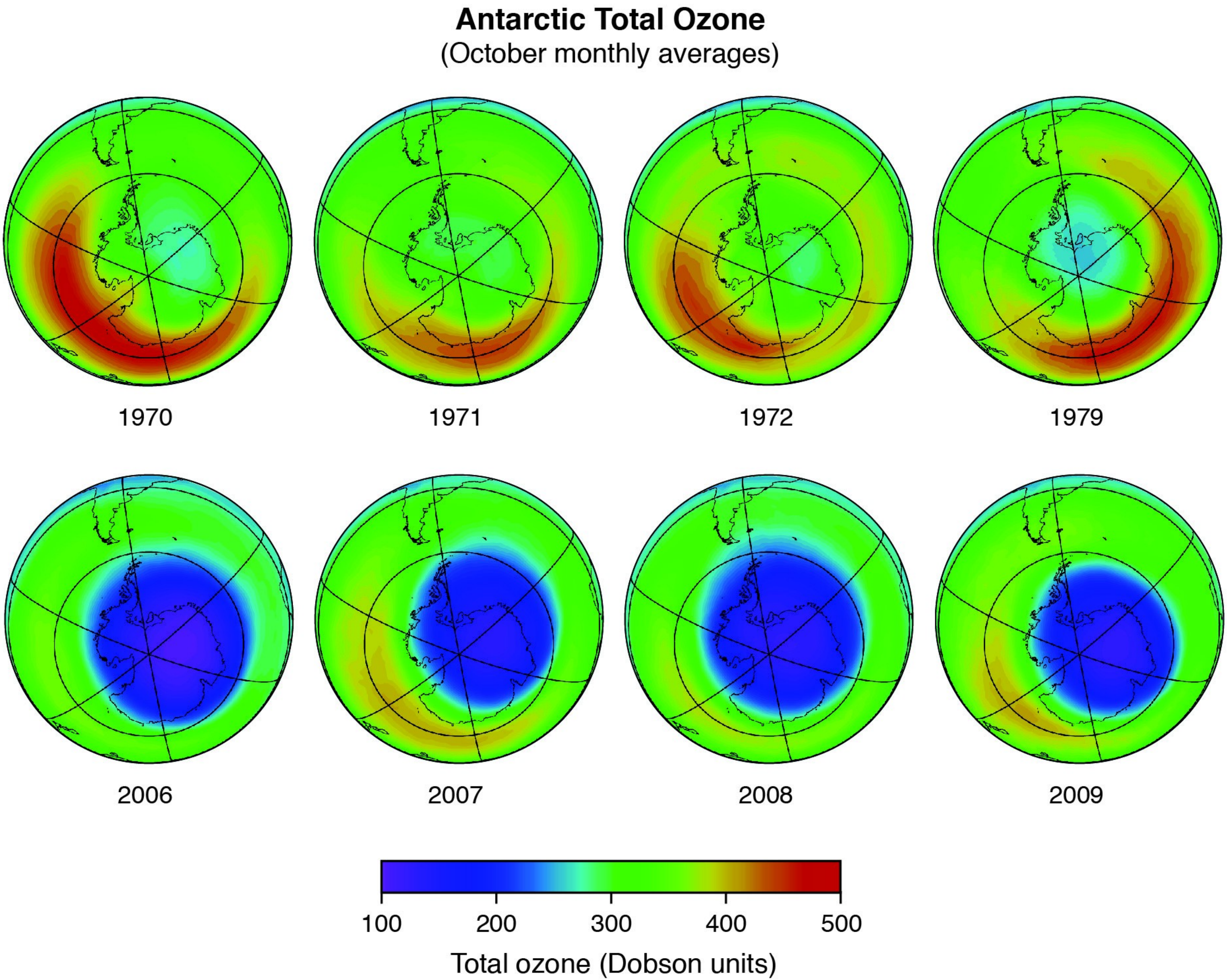
Discovery of Ozone Hole, Montreal Protocol



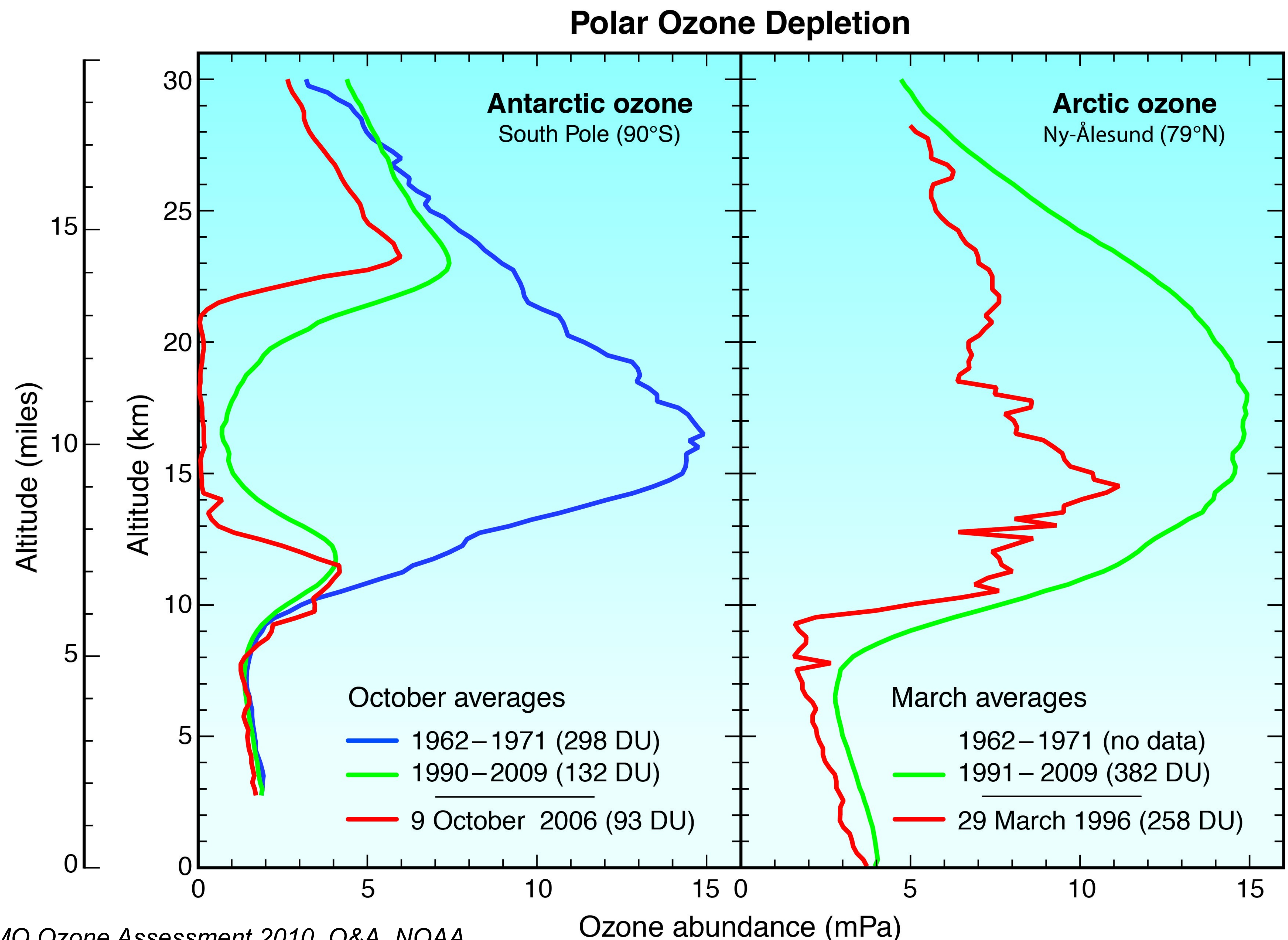
Antarctic Ozone Depletion



WMO Ozone Assessment 2010, Q&A, NOAA

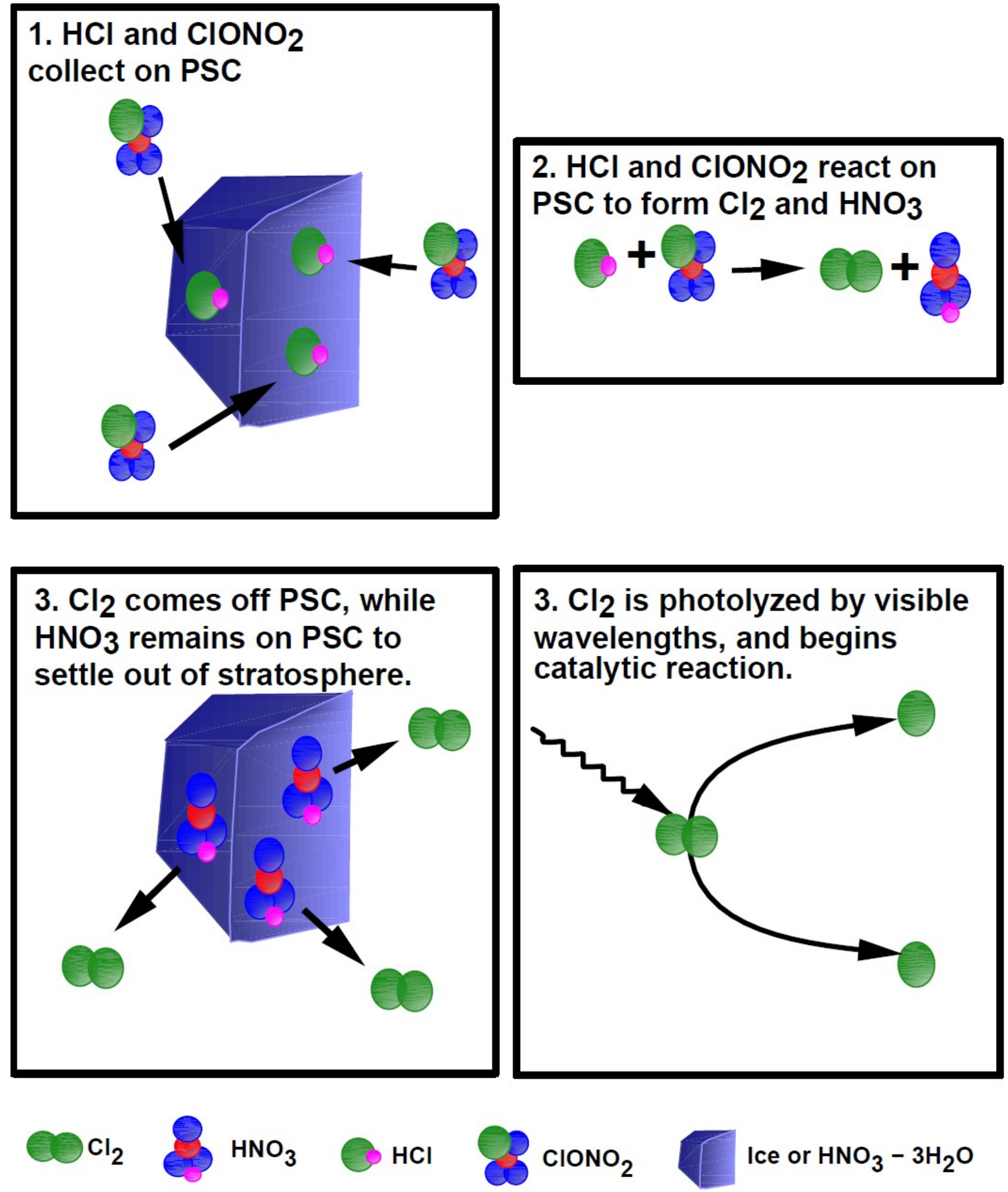

Antarctic Total Ozone
(October monthly averages)
1970
1971
1972
1979
2006
2007
2008
2009
100
200
300
400
500
Total ozone (Dobson units)

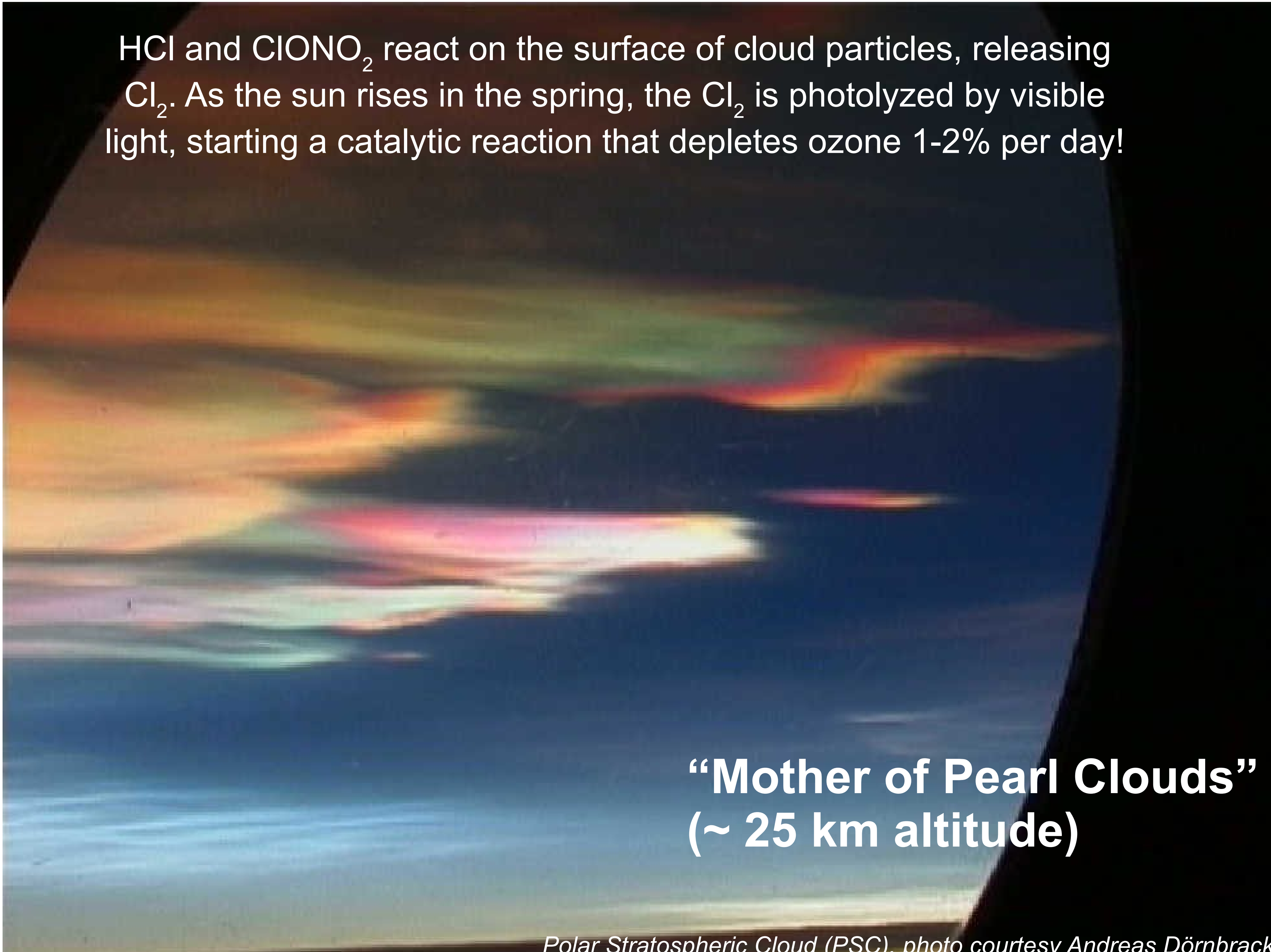
Why Ozone Hole?



WMO Ozone Assessment 2010, Q&A, NOAA

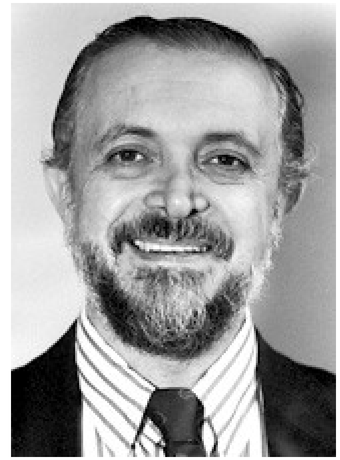
Polar Stratospheric Cloud Surface Reaction




HCl and ClONO$_2$ react on the surface of cloud particles, releasing Cl$_2$. As the sun rises in the spring, the Cl$_2$ is photolyzed by visible light, starting a catalytic reaction that depletes ozone 1-2% per day!
"Mother of Pearl Clouds"
(~ 25 km altitude)
Polar Stratospheric Cloud (PSC), photo courtesy Andreas Dörnbrack

The Players

1995 Nobel Prize in Chemistry to Molina, Rowland, Crutzen “for their work in atmospheric chemistry, particularly concerning the formation and decomposition of ozone”



Mario Molina

Sherwood Rowland

Paul Crutzen

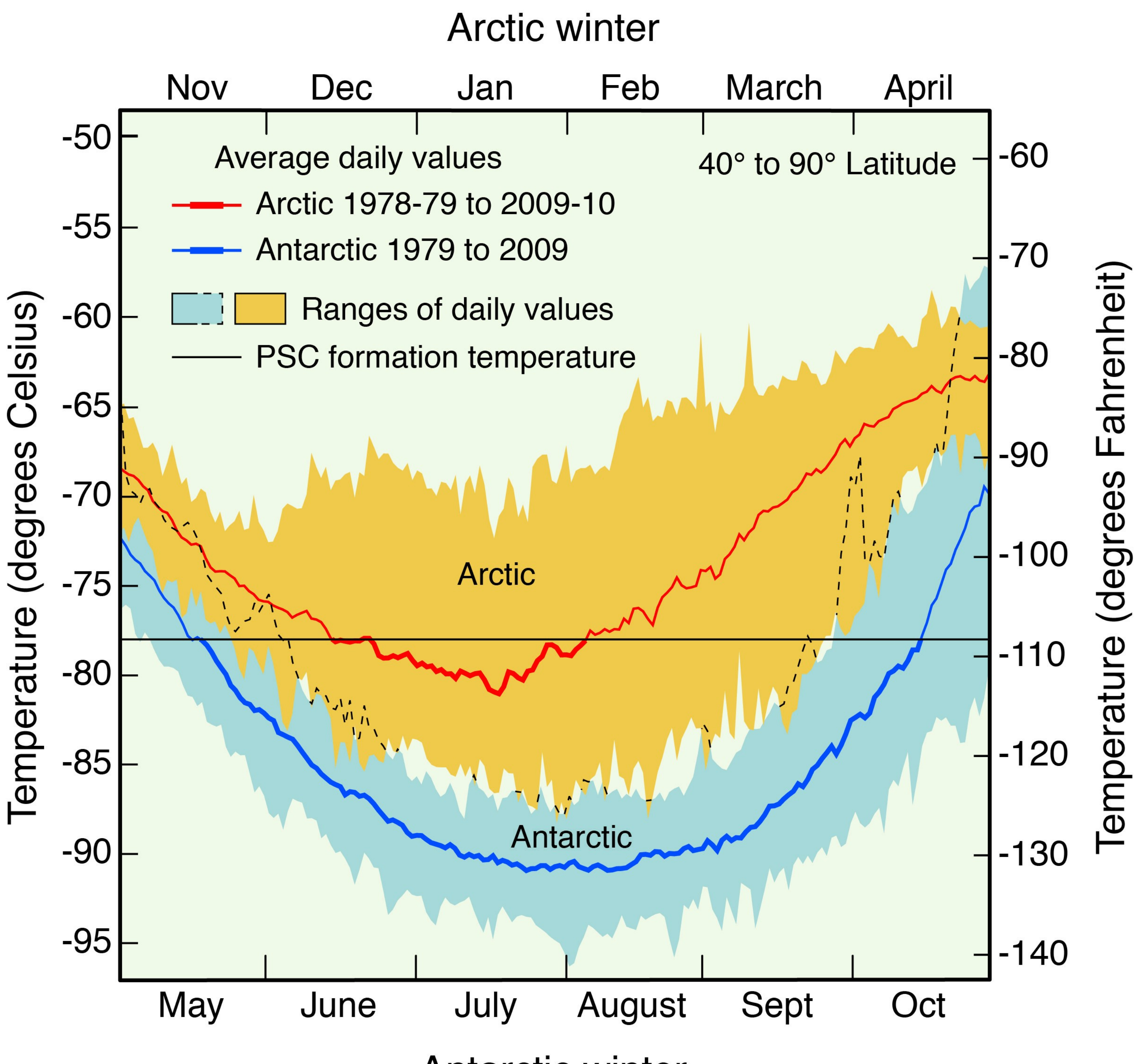
Discovery of Ozone Hole 1984/1985 by Shigeru Chubachi (left) and Joseph Farman, Brian Gardiner, Jonathan Shanklin (right)

Susan Solomon: Importance of heterogeneous reactions on the surface of PSCs

Arctic vs. Antarctic

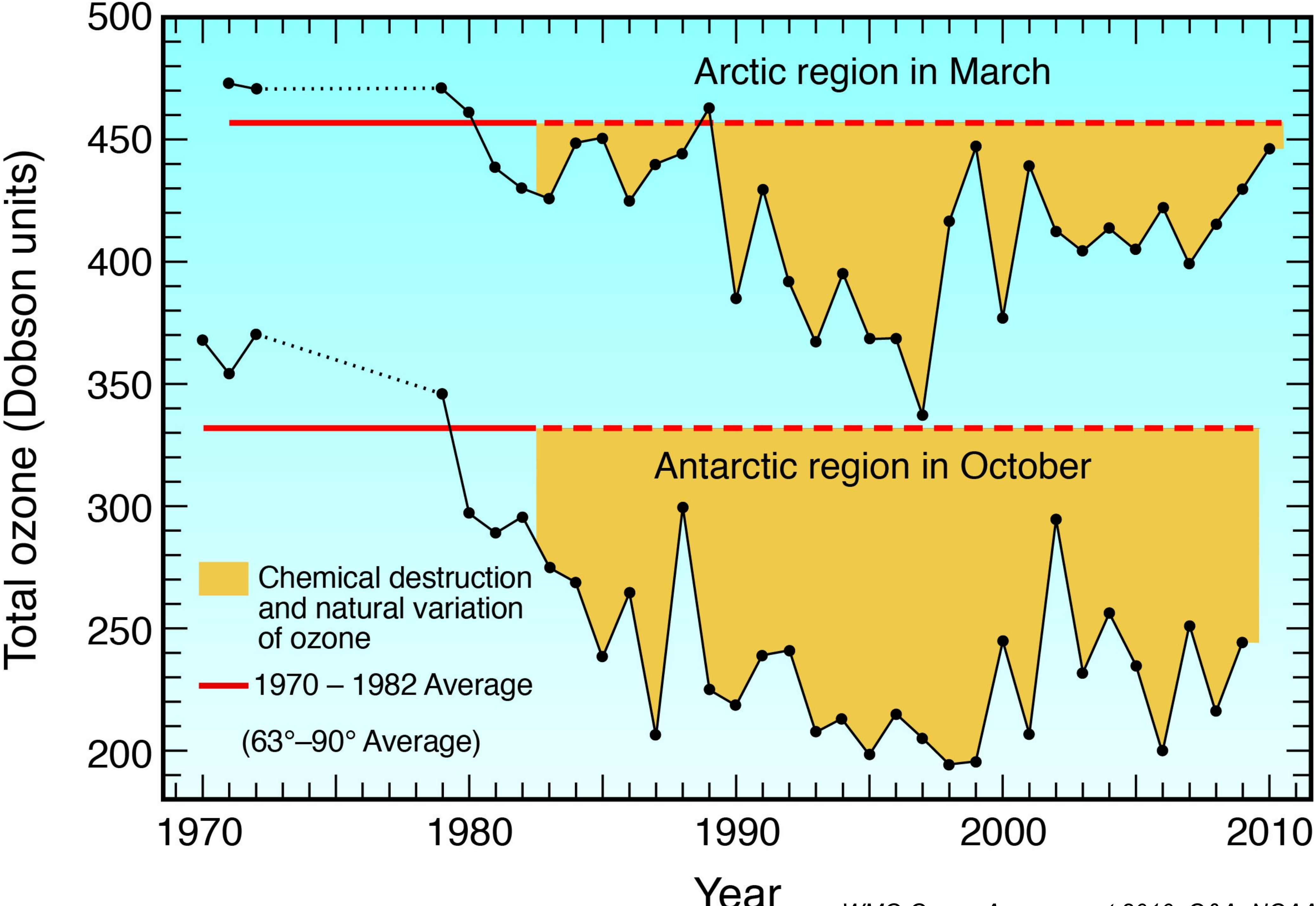
- During polar night lack of incoming solar radiation (i.e. lack of Ozone heating due to UV absorption) leads to strong cooling of stratospheric air
- The cold air tends to sink and spin up a gigantic vortex sitting over the polar cap of the winter hemisphere, with maximum winds ~60^o latitude
- Air inside strong polar vortex over Antarctic becomes isolated and cools sufficiently to produce PSCs → Ozone depletion & Ozone Hole
- Polar vortex over Arctic is frequently disturbed by atmospheric planetary waves that are generated at the Earth's surface by land/sea contrasts and topography and propagate up to the stratosphere
- These planetary waves can lead to a phenomenon called Sudden Stratospheric Warming (SSW), where temperatures inside the polar vortex increase by several 10s of degrees
- SSWs prevent air to be cold enough to produce wide-spread PSC coverage over the Arctic
- SSWs occur about every other year over Arctic, only 1 SSW has ever been recorded over Antarctic (in 2002)

Minimum Air Temperatures in the Polar Stratosphere



WMO Ozone Assessment 2010, Q&A, NOAA

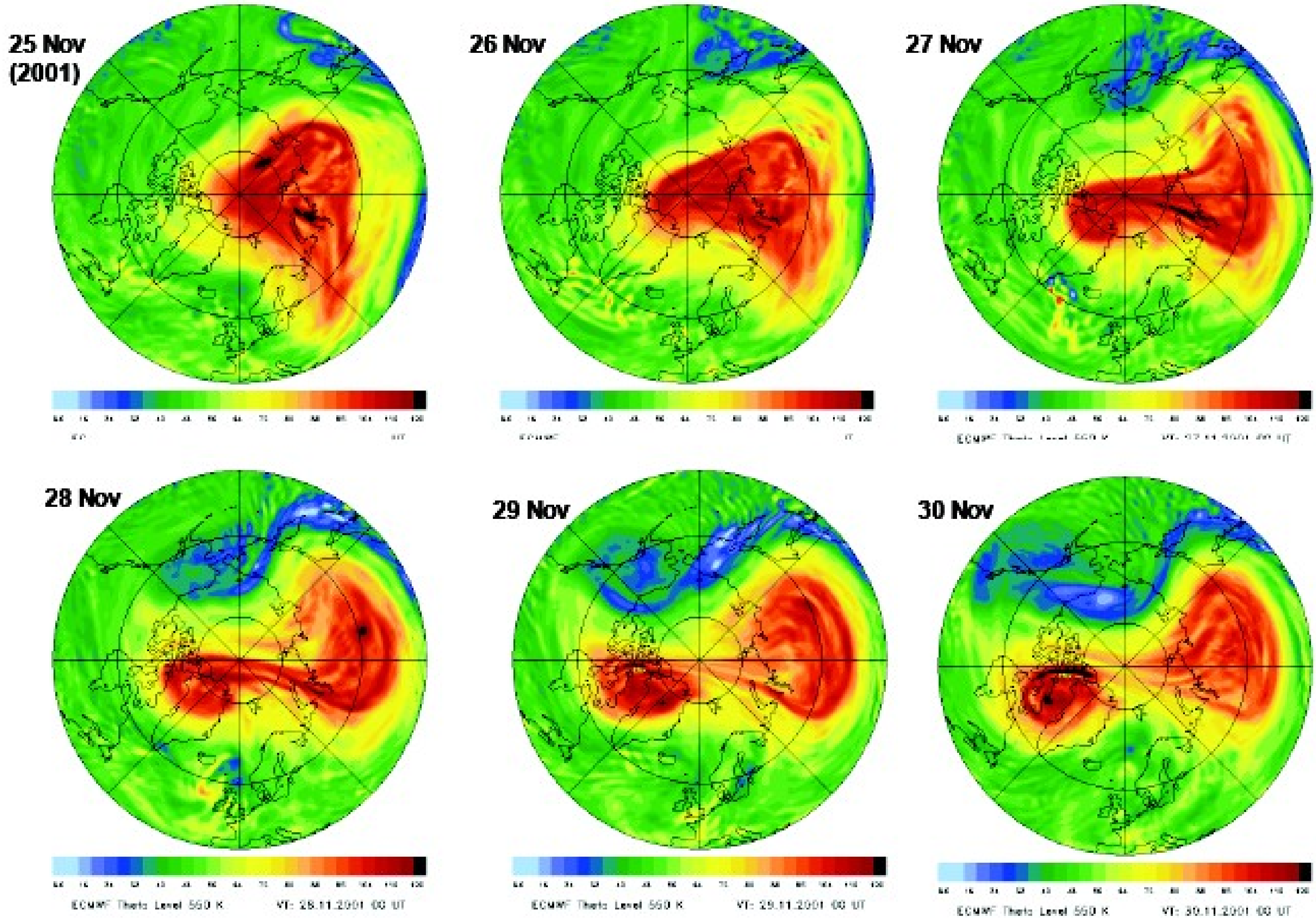
Average Total Ozone in Polar Regions



WMO Ozone Assessment 2010, Q&A, NOAA

Sudden Stratospheric Warming in November 2001

Split-up of the Arctic Polar Vortex, PV at 550 K (25 km)



Historical Notes: the Berlin Phenomenon

- Regular radiosonde observations by R. Scherhag (pronounce "Sharehug") from Berlin, Tempelhof (52°N) starting in 1951
- Scherhag observed in these radiosoundings an "explosive warming" of the stratosphere on January 27, 1952: "A warming of 30°C thus began on January 27 … at the 10-mb level ..." (from Labitzke & van Loon, 1999)

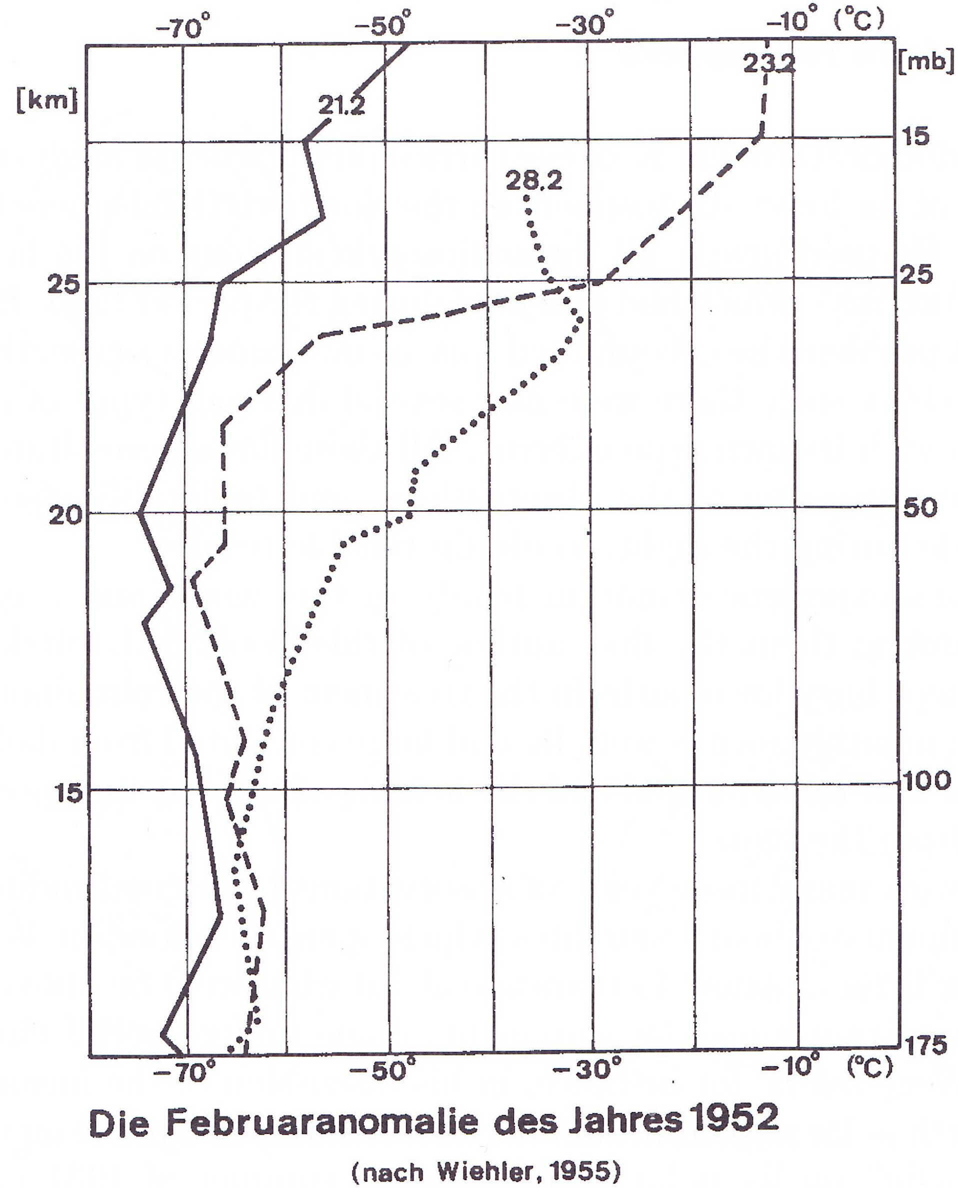
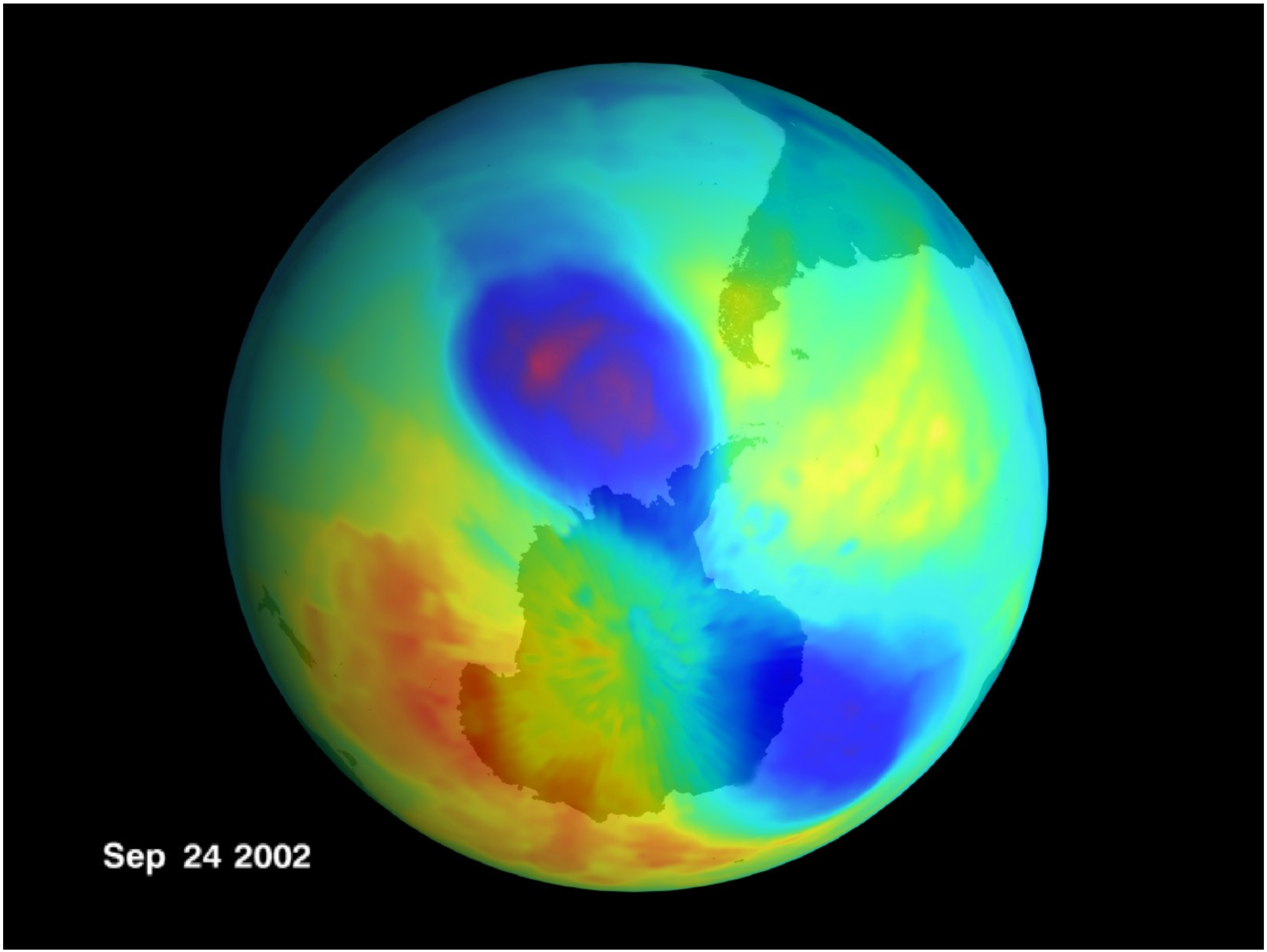
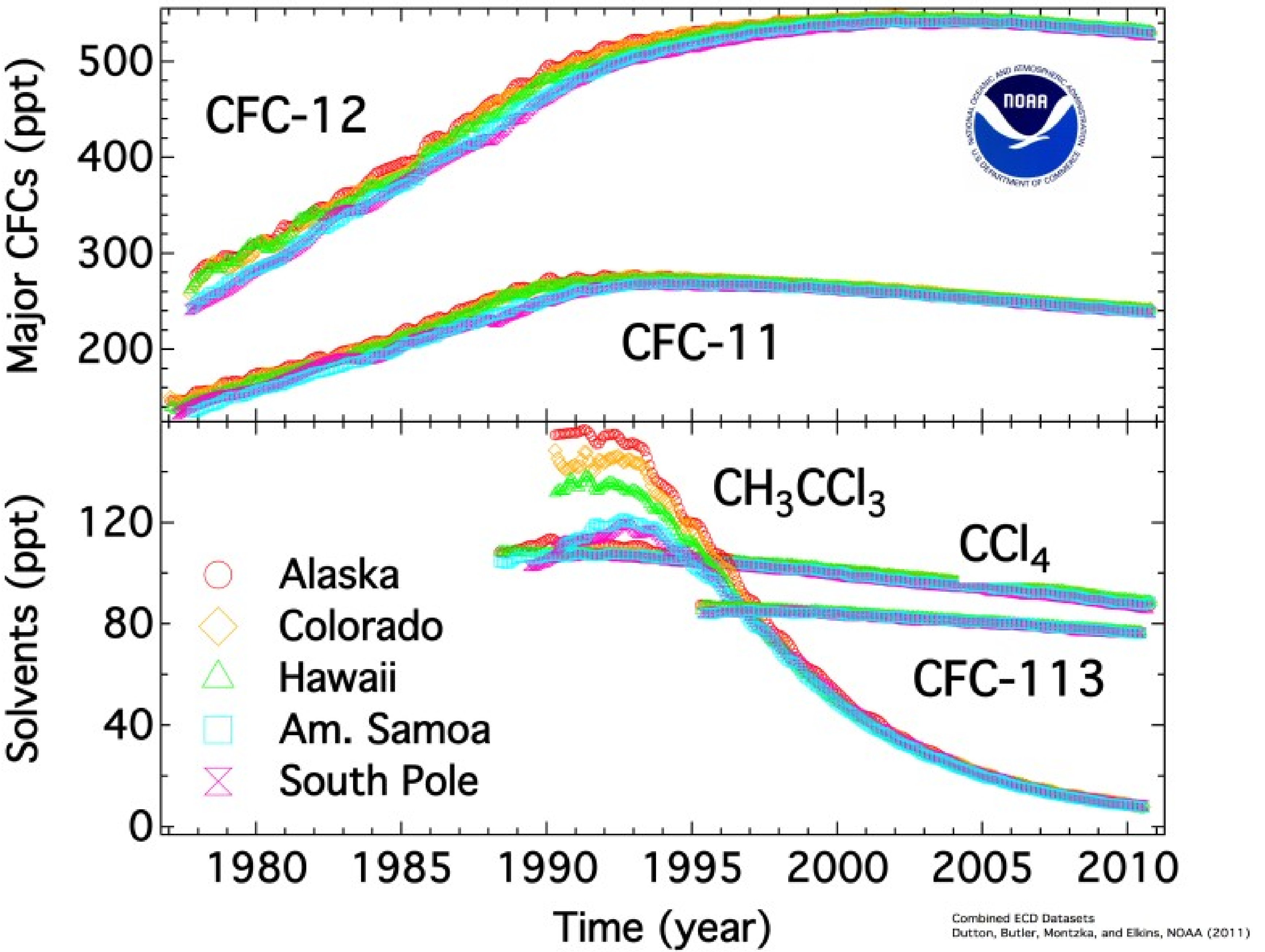


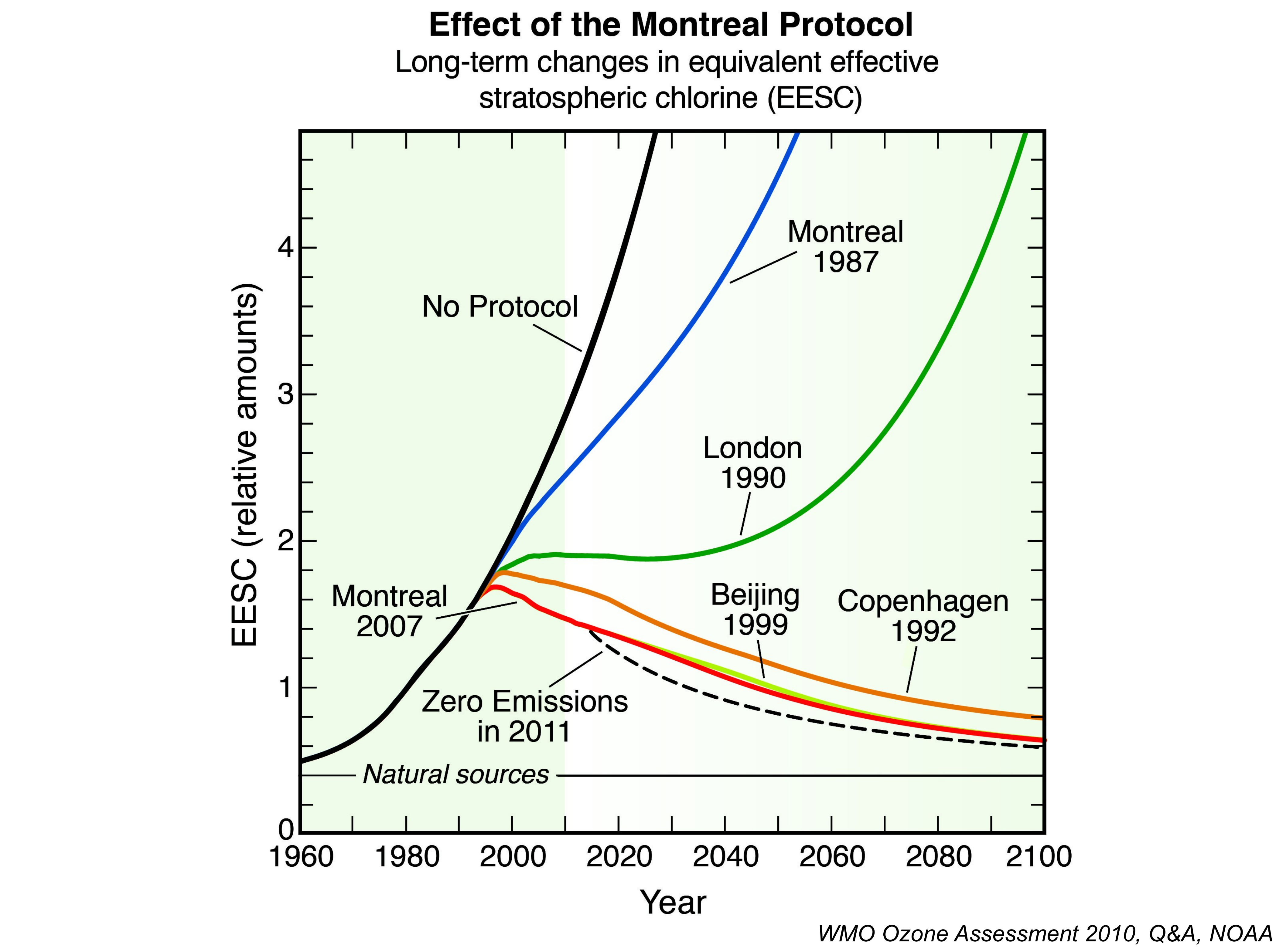
Fig. 1.4: The midwinter warming February 1952 (Wiehler 1955)

Split-up of the Antarctic Ozone Hole in 2002



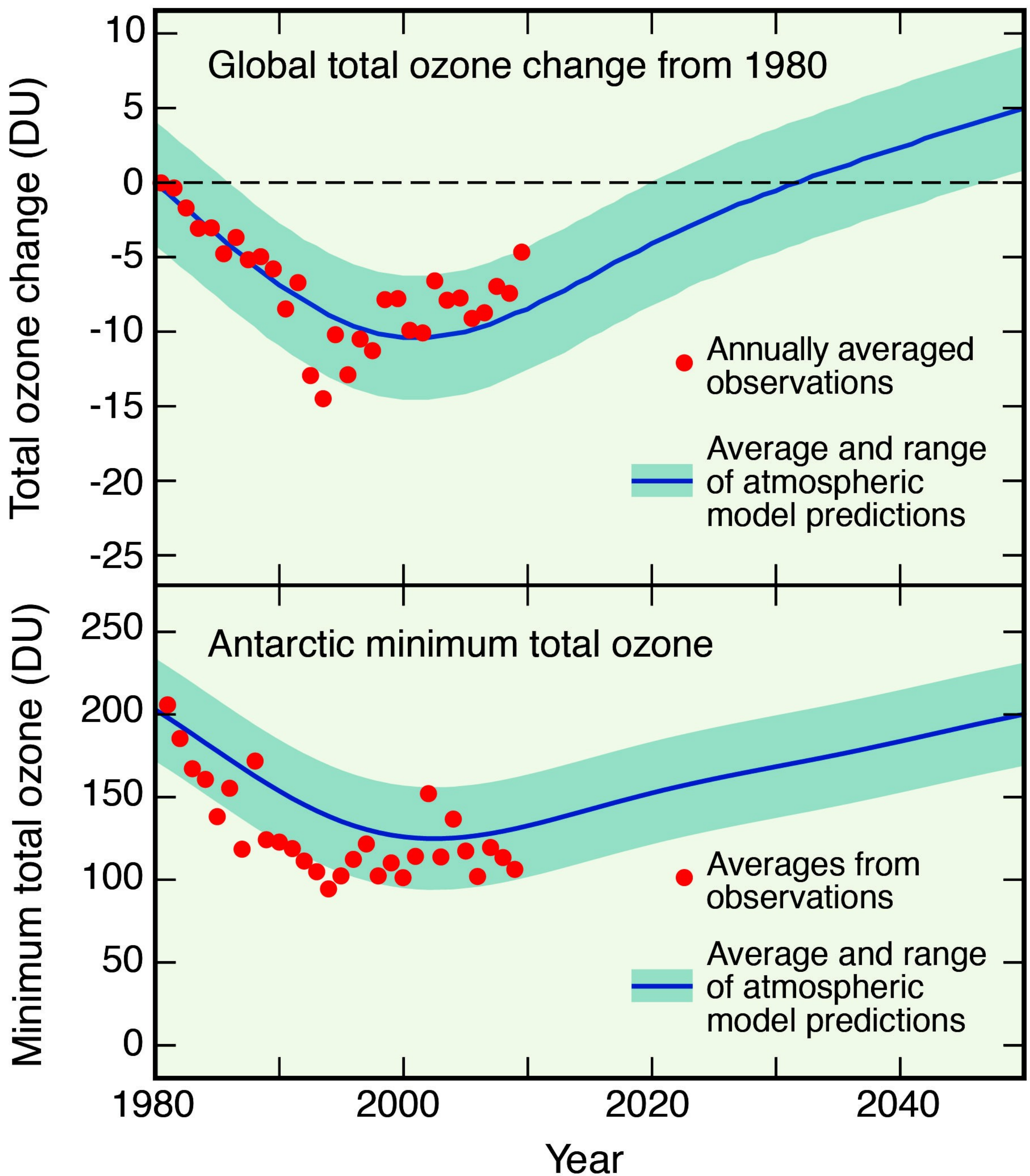
Effect of the Montreal Protocol: CFCs are meanwhile decreasing




Effect of the Montreal Protocol
Long-term changes in equivalent effective stratospheric chlorine (EESC)
EESC (relative amounts)
0
1
2
3
4
1960
1980
2000
2020
2040
2060
2080
2100
Year
No Protocol
Montreal 1987
London 1990
Montreal 2007
Beijing 1999
Copenhagen 1992
Zero Emissions in 2011
Natural sources
WMO Ozone Assessment 2010, Q&A, NOAA

Simulations of Stratospheric Ozone Depletion

Results from chemistry-climate models



Ozone Recovery expected by ~2050

WMO Ozone Assessment 2010, Q&A, NOAA

Increased CO_2 leads to stratospheric cooling(!) → more PSCs, slowed Ozone recovery

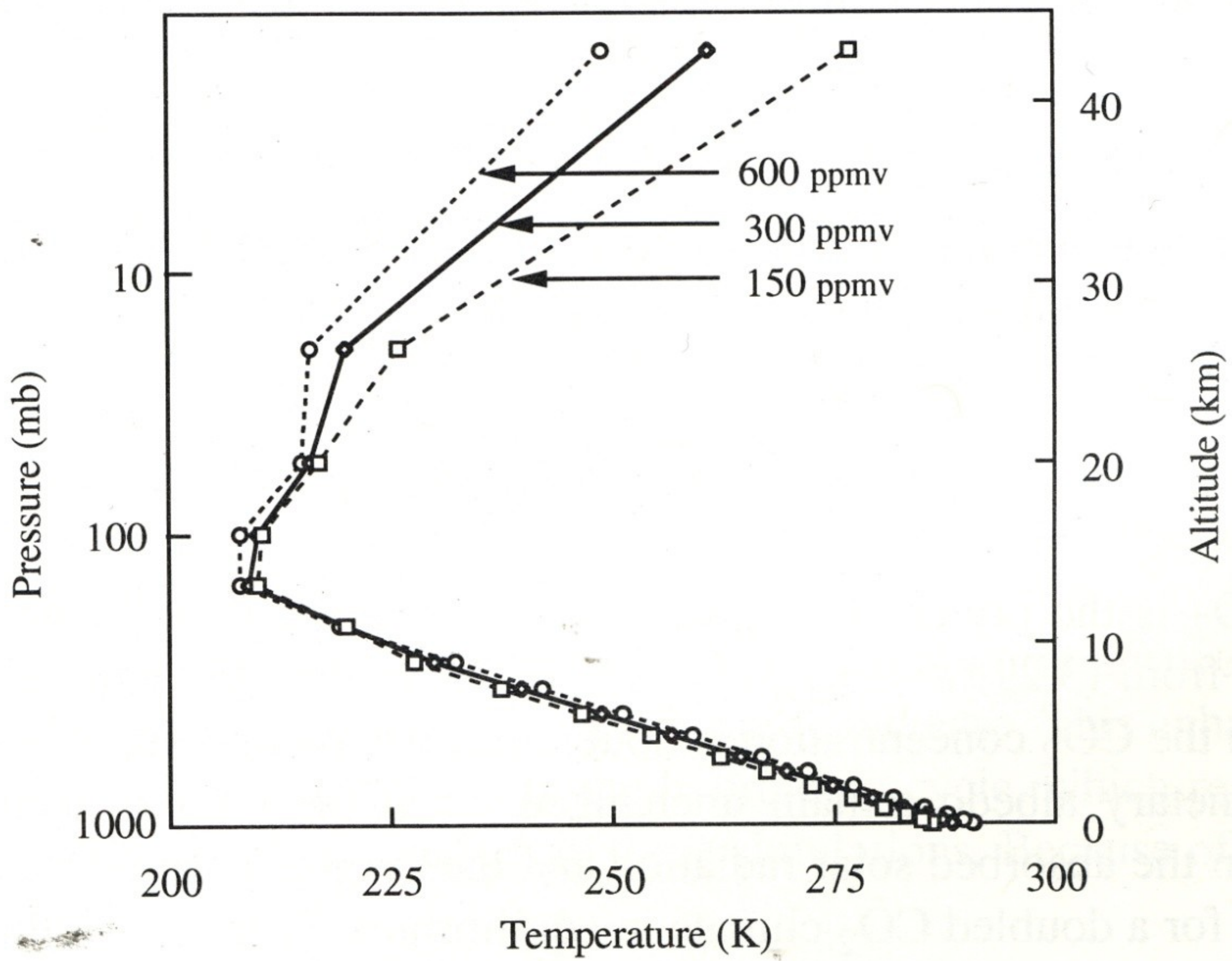


Fig. 12.7 Temperature profiles calculated with a one-dimensional radiative–convective equilibrium model for CO_2 at 150, 300, and 600 ppmv. [Data from Manabe and Wetherald (1967). Reprinted with permission from the American Meteorological Society.]

Lessons Learned

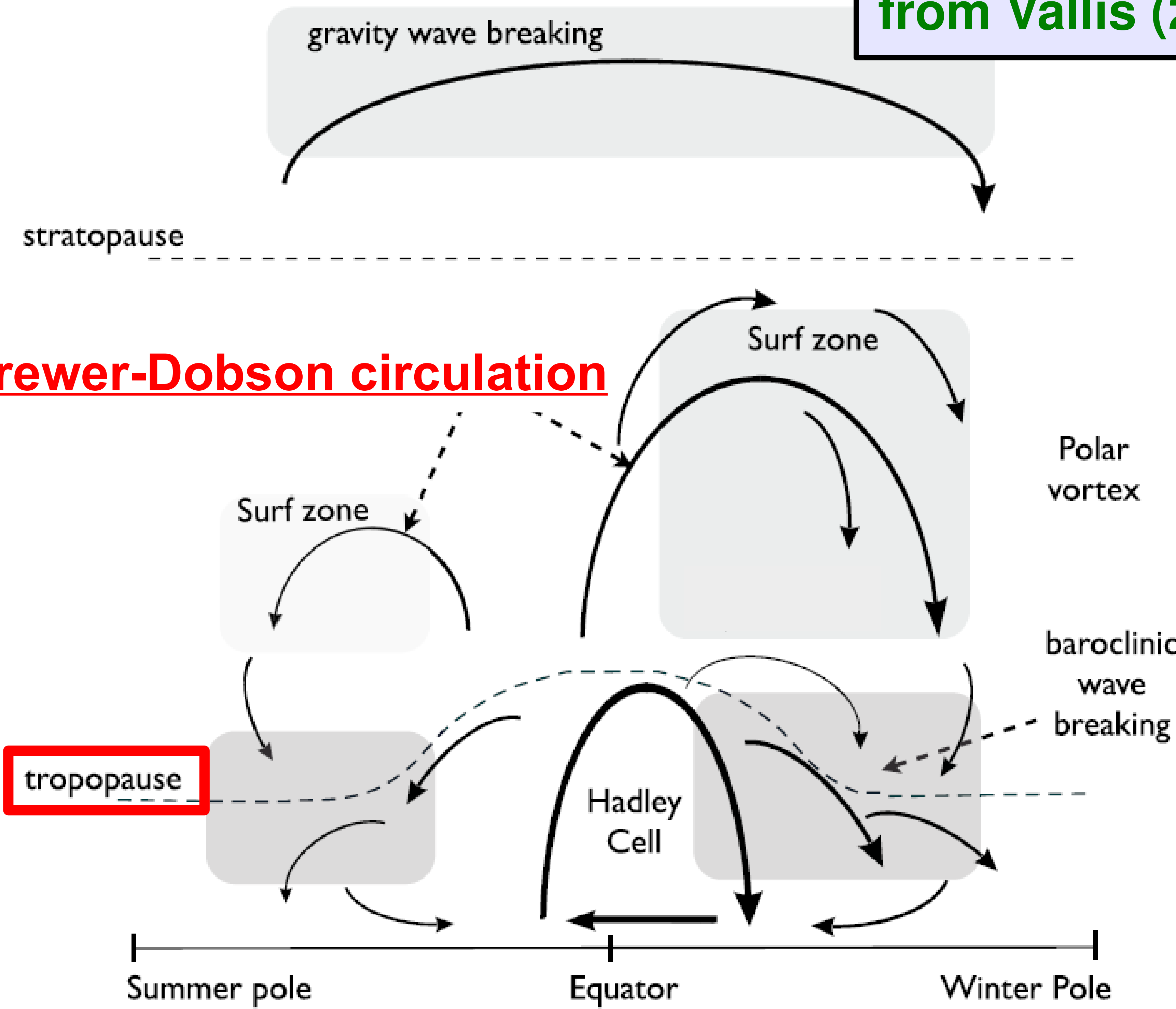
- Adding trace gases to the atmosphere with long lifetimes can be dangerous
- Monitor atmospheric constituents, double-check data
- Montreal Protocol (and its successors) worked based on international scientific assessments
- Don't underestimate human ability to invent new technology if needed (without running into economical crisis)
- A model for dealing with Climate Change?

Bonus Material: Stratospheric Transport Circulation

- How can CFCs, which are emitted by human activity (mostly in Northern Mid-latitudes) reach the Antarctic Stratosphere?
- How does Water Vapor (needed to produce PSCs) enter the Stratosphere?
- Why is there less Ozone in the tropics (despite more incoming solar radiation) than in the polar regions?

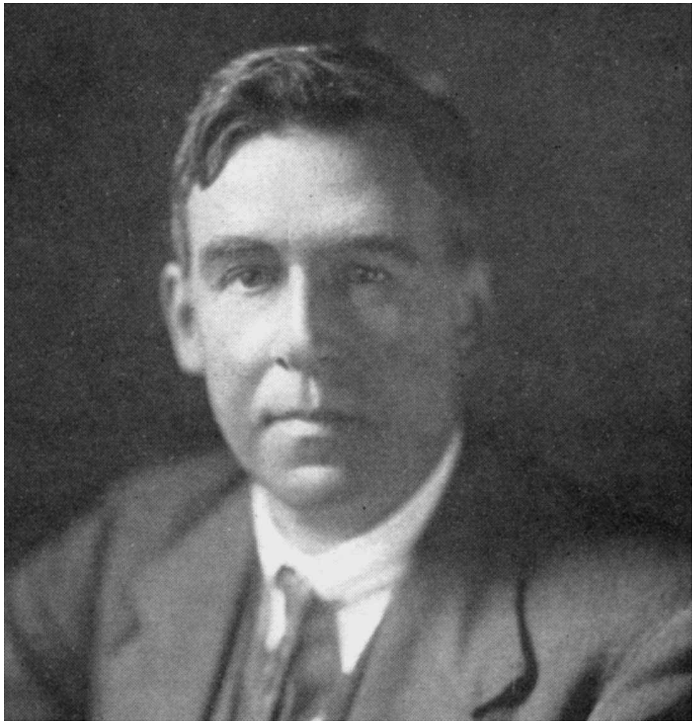
from Vallis (2006)

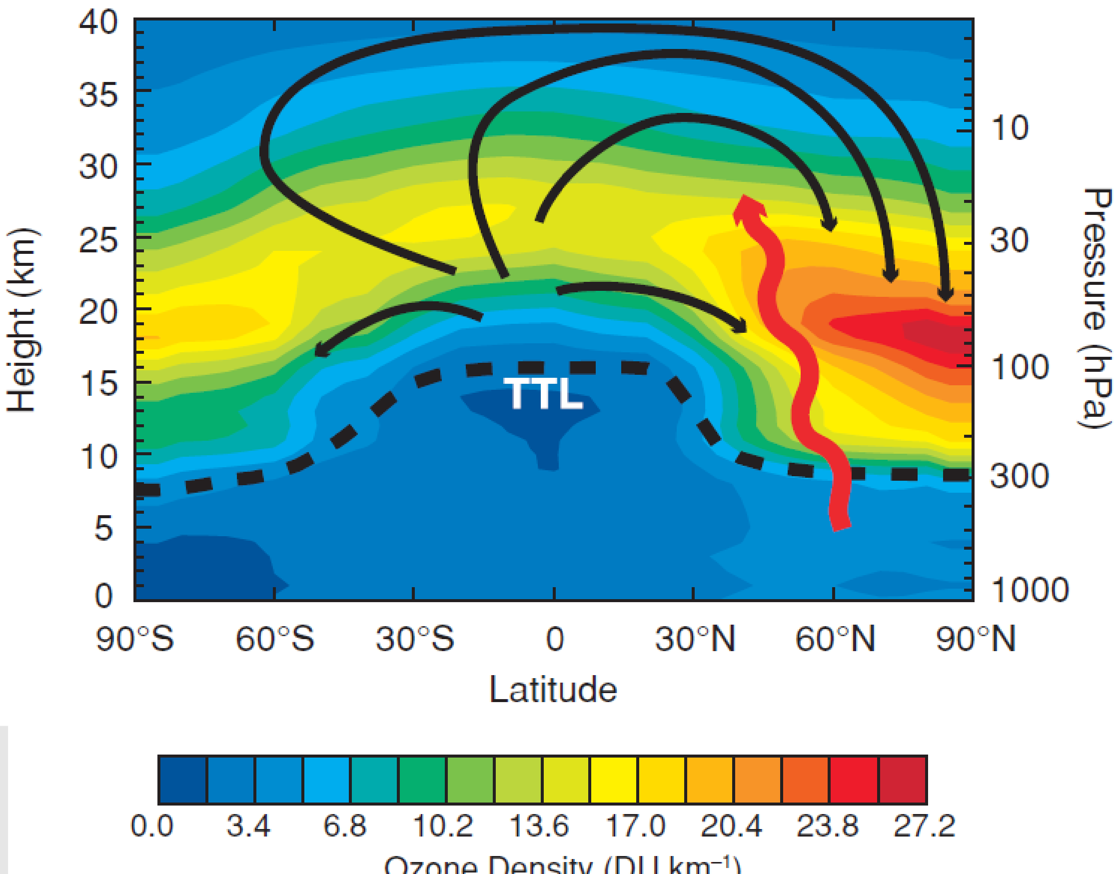
Brewer-Dobson circulation



Discovering the Stratospheric Circulation

Dobson, Harrison, Lawrence (1929): *"The only way in which we can reconcile the observed high ozone concentration in the Arctic in spring and the low concentration in the tropics ... would be to suppose a general slow poleward drift in the highest atmosphere with a slow descent of air near the poles ..."*





But: Dobson didn't have vertical ozone profiles then and basically discarded this possibility.

IPCC/TEAP special report, 2005

Discovering the Stratospheric Circulation

Dobson, Brewer, Cwilong (1946, Bakerian Lecture): *showed some of the first frost point profiles (obtained by Brewer and Cwilong) measured by a frost point hygrometer → the stratosphere was found to be very dry.*

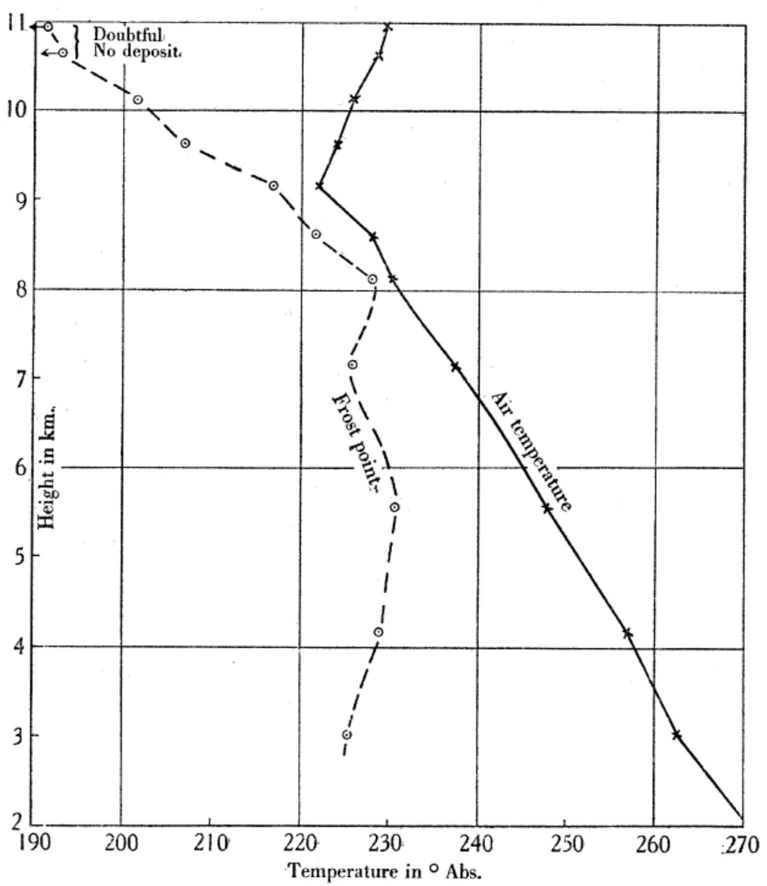
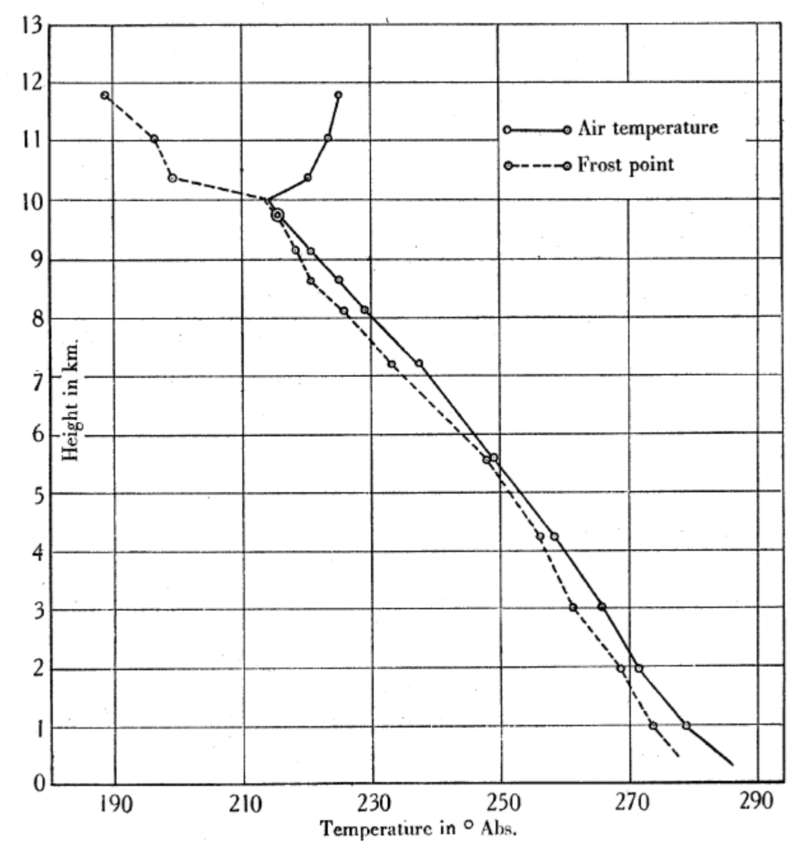


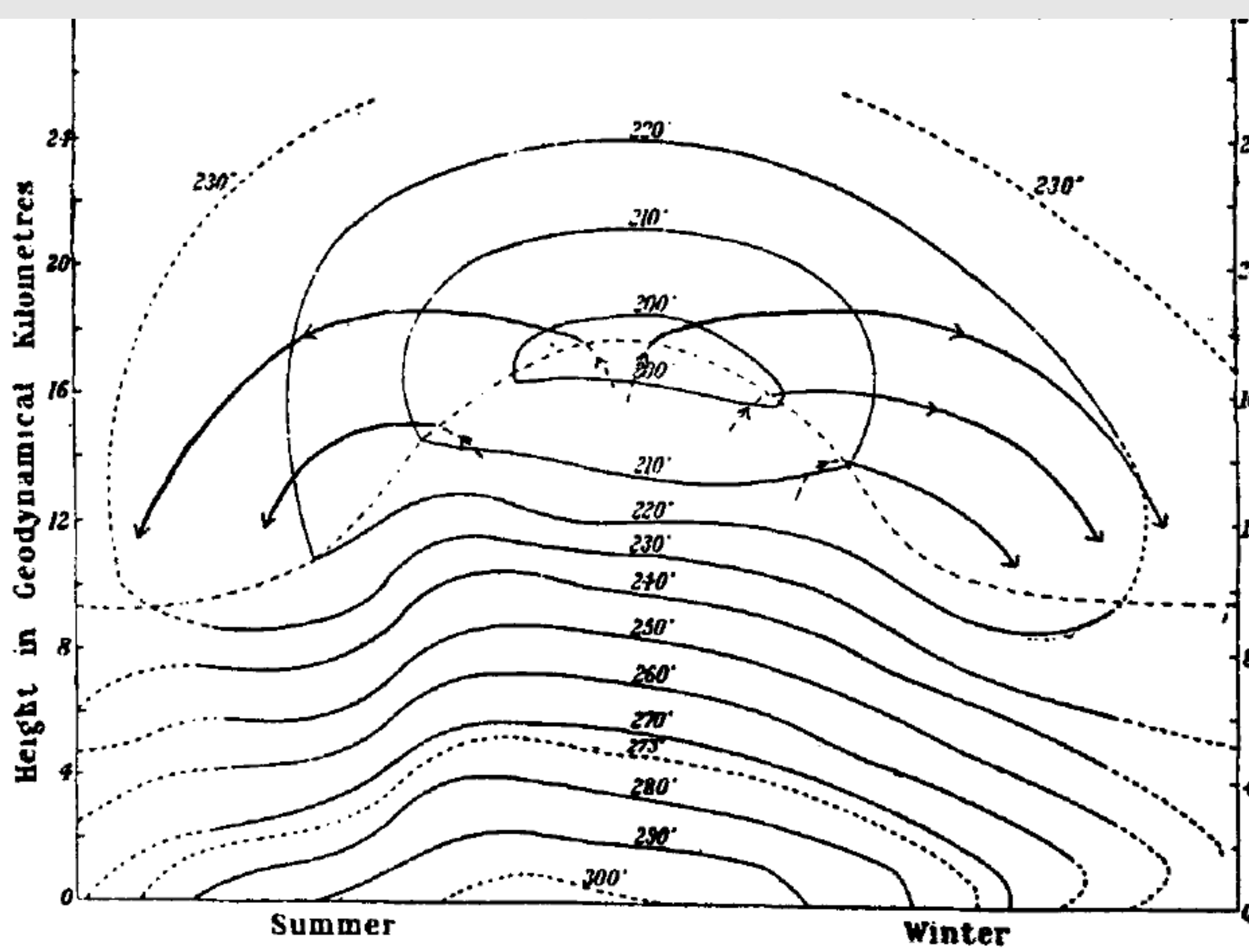
FIGURE 4. Frost-points and air temperatures observed on the first ascent when humidities were measured in the stratosphere, Boscombe Down, 22 December 1943.



rost-points and air temperatures observed on Boscombe Down, 30 May 1945, 0 G.M.T. The frost-point at the top is the lowest yet observed.

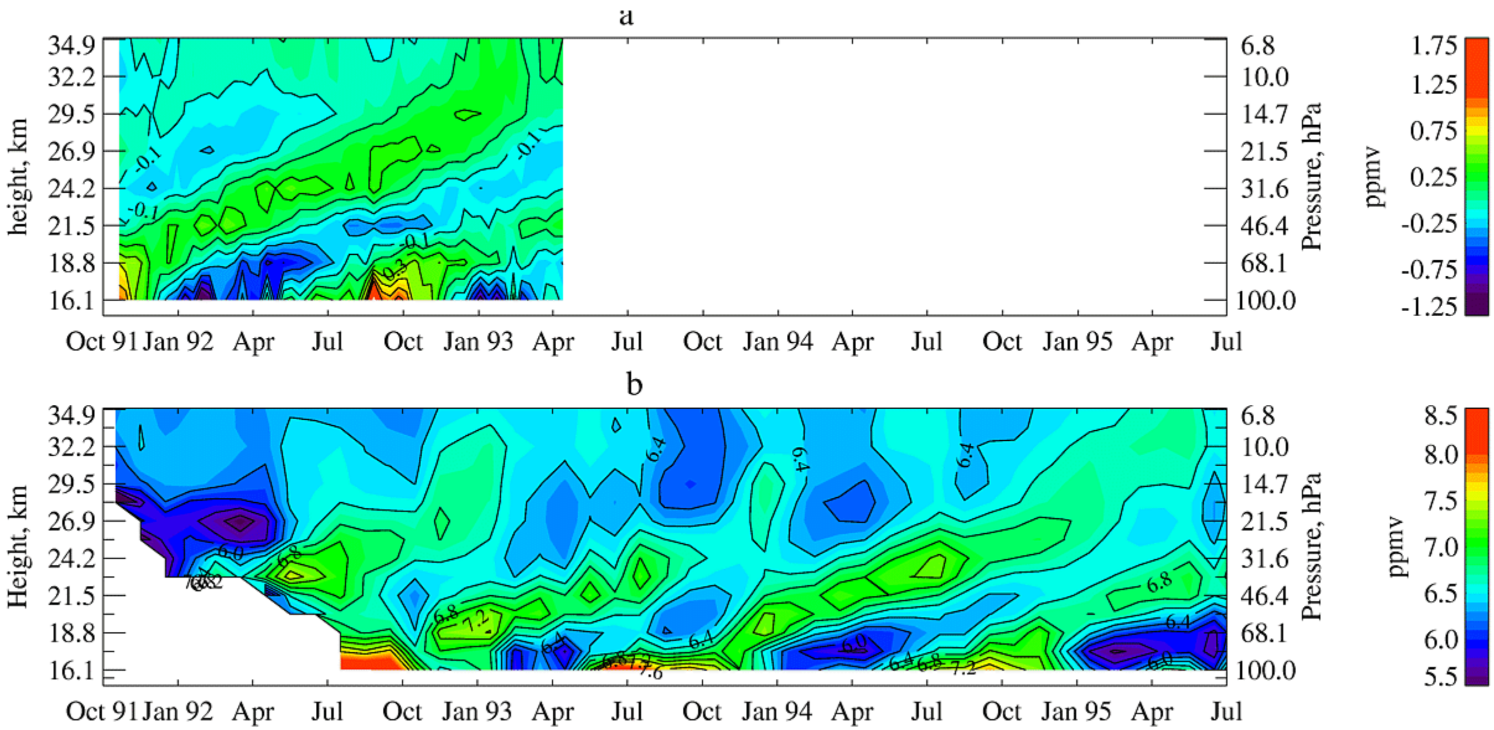
Discovering the Stratospheric Circulation

Brewer (1949): *"... dryness is maintained by a slow circulation of the air in which air rises at the equator moves poleward in the stratosphere and then descends into the troposphere in temperate and polar regions ..."*

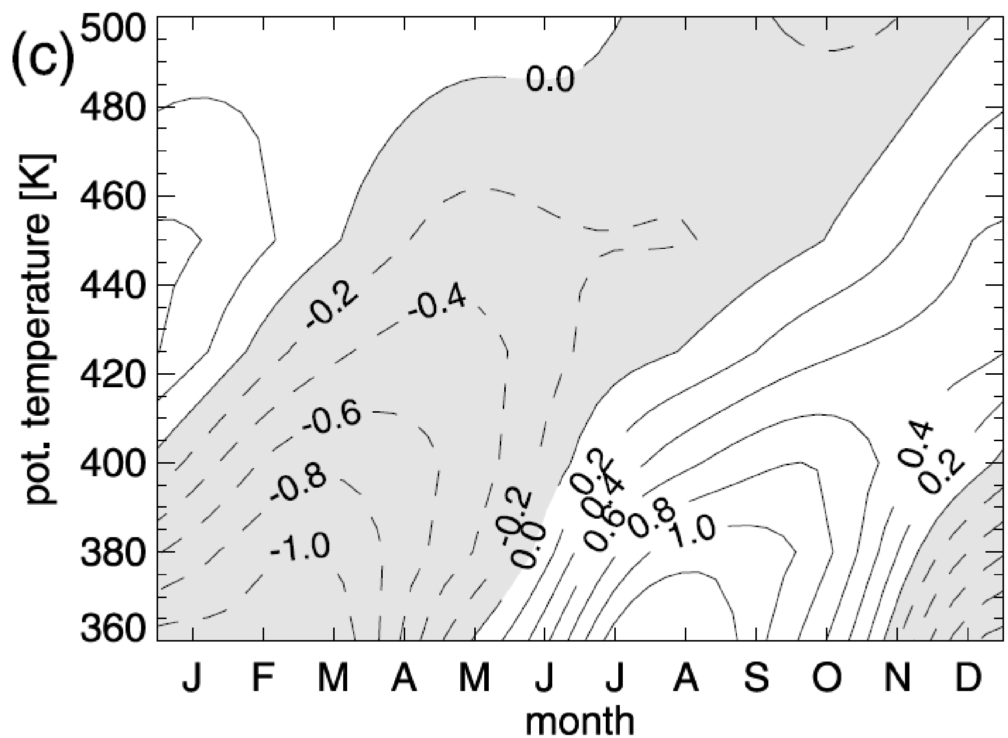


Isotherms over the Globe

FIG. 5. A supply of dry air is maintained by a slow mean circulation from the equatorial tropopause.



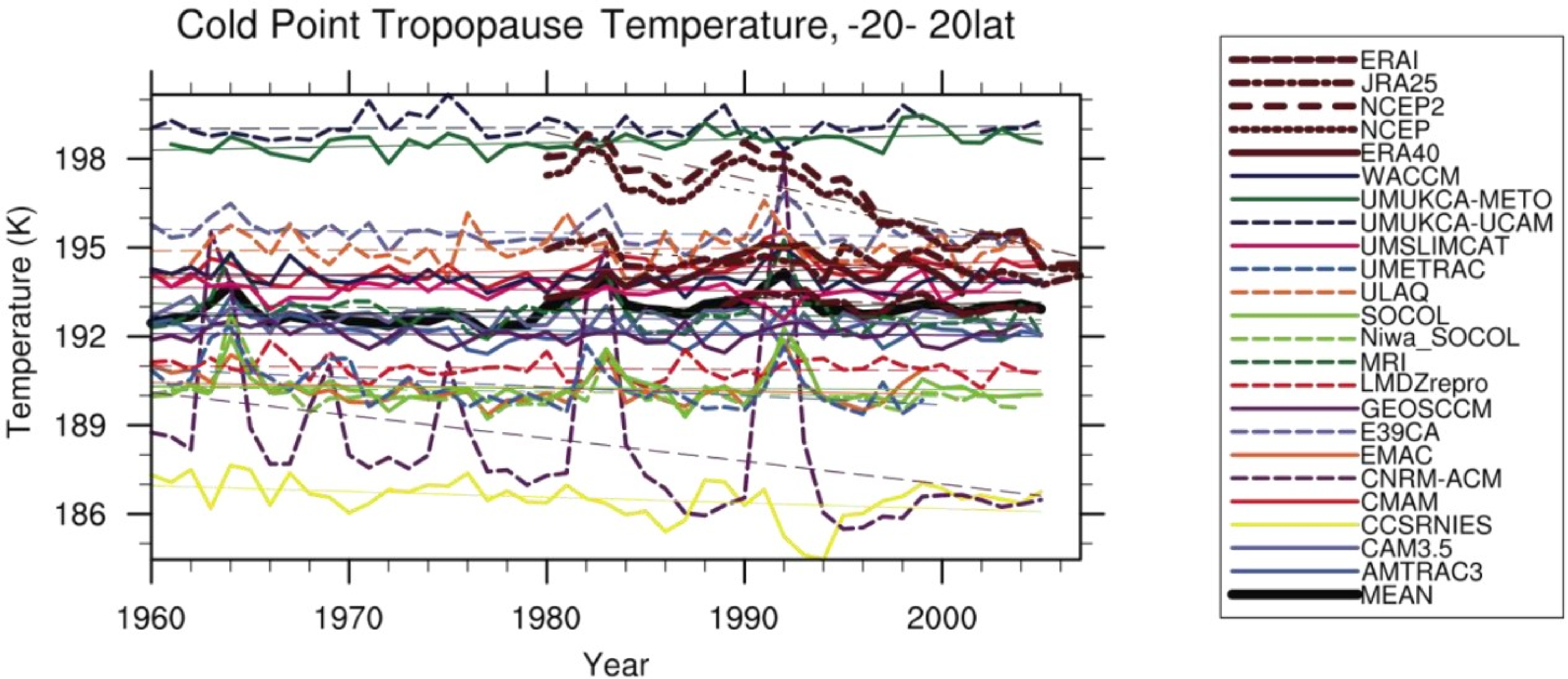
(Mote et al., 1996)



Tape Recorder

(Fueglistaler et al. 2009)

SPARC CCMVal Report (Gettelman et al., 2010)



	MEAN	AMTRAC	CAM3.5	CCSRNIES	CMAM	CNRM-ACM	EMAC	E39CA	GEOSCCM	LMDZ-R	MRI	N-SOCOL	SOCOL	ULAQ	UMETRAC	UMSLIMCAT	UKCA-UCAM	UKCA-METO	WACCM	ERA40	NCEP	NCEP2	JRA25	ERAI
GSUM	0.5	0.4	0.5	0.3	0.7	0.1	0.3	0.5	0.5	0.4	0.5	0.4	0.4	0.6	0.4	0.6	0.5	0.5	0.6	1.	0.5	0.4	0.7	0.5
variance GV	0.8	0.8	0.9	0.8	0.9	0.	0.8	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.9	1.	0.8	0.8	0.9	0.8
correl. GC	0.3	0.3	0.4	0.2	0.5	0.4	0.2	0.4	0.4	0.3	0.5	0.3	0.3	0.4	0.4	0.5	0.6	0.5	0.3	1.	0.6	0.5	0.4	0.3
mean GM	0.4	0.	0.2	0.	0.7	0.	0.	0.4	0.1	0.	0.3	0.	0.	0.6	0.	0.6	0.	0.	0.7	1.	0.	0.	0.7	0.5

Grade: 0., 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.